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Interpreting quantum nonlocality as platonic information

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INTERPRETING QUANTUM NONLOCALITY AS PLATONIC INFORMATION

A Thesis

Presented to

The Faculty of the Department of Philosophy

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Arts

by

James C. Emerson

May 2009

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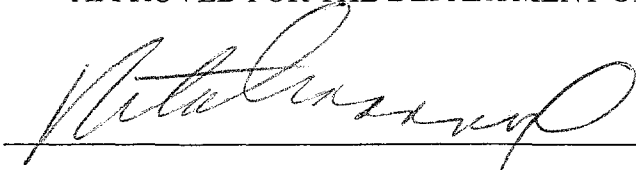
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INTERPRETING QUANTUM NONLOCALITY AS PLATONIC INFORMATION

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ABSTRACT

INTERPRETING QUANTUM NONLOCALITY AS PLATONIC INFORMATION

by James C. Emerson

The “hidden variables” or “guiding equation” explanation for the measurement of quantum nonlocality (entanglement) effects can be interpreted as instantiation of Platonic information. Because these Bohm-deBroglie principles are already external to the material objects that they theoretically affect, interpreting them as Platonic is feasible.

Taking an approach partially suggested by Quantum Information Theory which views quantum phenomena as sometimes observable-measurable information, this thesis defines hidden variables/guiding equation as information. This approach enables us to bridge the divide between the abstract Platonic realm and the physical world. The unobservable quantum wavefunction collapse is interpreted as Platonic instantiation. At each interaction, the wave function for a quantum system collapses. Instantly, Platonic information is instantiated in the system.

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Introduction

Quantum mechanics (QM) has posed philosophical problems from its beginnings. Although its mathematics is often understood as representative of probabilistic conditions, the question still arises “whether ... to what degree, and in what sense [do quantum states, for example] correspond to actual physical states?”¹ Discussions about quantum phenomena frequently involve questions about the quantum state of a system. Some philosophers of science argue that quantum states represent potential, not reality.² But, quantum nonlocal entanglement, one of these problematic states, is a demonstrated fact. Quantum entangled³ systems and particles are probabilistically correlated across distances. A change to one is immediately associated with a corresponding change in the other.

A few philosophers of science and theoretical physicists explain these apparently counter-intuitive phenomena as evidence of an acausal relational rather than causal

¹ “A quantum state is part of the mathematic[s] ... that enables a rigorous (numerical) assessment of our probabilistic expectations concerning the outcomes of ... experiments.... The role of measuring instruments *makes quantum states strictly a mathematical tool of our mental expectations* [my italics].... ‘Quantum states’ ... relate to measurements and predictions concerning observations pertaining strictly to certain parts of measuring instruments impacted by their interaction with quantum objects ... *quantum states relate physically to no properties of quantum objects at any point* [my italics].” Arkady Plotnitsky, “A New Book of Numbers: On the Precise Definition of Quantum Variables and the Relationships between Mathematics and Physics in Quantum Theory,” *Foundations of Physics* 36 (January 2006), 53–54.

² “The quantum state may be construed ... as representing a network of potentialities ... a field of potentially possible and not actually existing events.” Vassilios Karakostas, “Forms of Quantum Nonseparability and Related Philosophical Consequences,” *Journal for General Philosophy of Science* 35 (2004), http://philsci-archive.pitt.edu/archive/00002152/01/V.E._KARAKOSTAS.doc (accessed October 4, 2008)

³ Erwin Schrodinger introduced the expression “entanglement” in 1935. In this thesis, quantum “nonlocality” and quantum “entanglement” are used synonymously.

dynamic world. Others propose an atemporal, redefinition of nonlocality-as-local, and superluminal (faster-than-light contact) models. This thesis takes another approach.

In the unending debate between empiricism and idealism, modern interpretations of theoretical physics and mathematics sometimes echo Platonism. This thesis proposes a new Platonic basis for quantum nonlocality, operating as “nonlocal hidden variables” at the quantum-level.

Many mathematicians and philosophers of mathematics promote or accept the external, Platonic existence of mathematical objects. Some point to Quine’s and Putnam’s “indispensability argument for mathematical realism,” asserting that the existence of mathematical objects is as acceptable as that of the physical objects they describe.⁴ Most accept that adequate explanations of physically verified phenomena frequently rely upon mathematical objects.

However, few modern physicists incorporate Platonism in their models of physical systems.⁵ Unlike electromagnetic fields, particle hierarchies, wave function effects, and spacetime effects including gravity, time dilation, and black holes, Platonic entities are not things that could be experimentally verified or conventionally applied to

⁴ Quine and Putnam argued that “the indispensability of mathematics to empirical science gives us good reason to believe in the existence of mathematical entities ... entities such as sets, numbers, functions and such [are] indispensable to our best scientific theories ... we ought to be committed to the existence of these mathematical entities. To do otherwise is to be guilty of what Putnam has called ‘intellectual dishonesty.’ Moreover, mathematical entities are seen to be on an epistemic par with the other theoretical entities of science, since belief in the existence of the former is justified by the same evidence that confirms the theory as a whole (and hence belief in the latter).” Mark Colyvan, “Indispensability Arguments in the Philosophy of Mathematics,” *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, (Stanford: Metaphysics Research Lab, 2008), <http://plato.stanford.edu/archives/fall2008/entries/mathphil-indis/> (accessed September 27, 2008)

⁵ For more about contemporary physical Platonism, see “Physical Platonism,” in this thesis.

given equations of physics.⁶ And, they cannot be incorporated into an experimentally predictive model. However many theoretical physicists accept mathematically-based but presently untestable non-Platonic theoretical entities and phenomena such as the Higgs field and quantum fluctuations, causality-modifying twistors, mbranes, and others.

Following their lead, this thesis suggests that measured evidence of a quantum nonlocality (systems entanglement) can be explained as instantiations of external Platonic entities. The key elements of the Platonic model are represented in Figure 1.

A few philosophers and physicists have embraced a new restatement of QM, Quantum Information Theory (QIT), which interprets quantum phenomena as information. Some key QIT concepts are incorporated into this thesis⁷ expressed as Platonic information. Applying the notion of Platonic information, modern theoretical physics could be explained at many levels:⁸ 1) expressing a modern physical theory such as quantum mechanics (QM) in Platonic informational terms, 2) expressing a subject within QM such as quantum nonlocality in Platonic informational terms, or 3) re-expressing an existing explanation (deBroglie-Bohmian “hidden variables,” also referred to as a “pilot wave” or “guiding equation”) of a subject within QM (such as quantum nonlocality) in Platonic informational terms. This thesis focuses on the last.

The key question for any explanation of QM nonlocality, including this one, is

⁶ However, for a description of a quantum phenomenon that is nearly Platonic, see the section “Demonstrated Physical Platonism,” in this thesis.

⁷ Some QIT concepts are rejected. Unlike QIT, for this thesis, I do not reject hidden variables but instead attempt to explain them.

⁸ Although more granular levels of explanation are conceivable, I’ve stopped at these three levels for practical reasons.

“how is the change in one member of an entangled pair (or triplet or more) transferred to- or made to occur in the other member(s)? The variety of possible answers reflects the diversity in contemporary theoretical physics. This thesis proposes a Platonic mechanism.

Defining “Platonic forms” or mathematically “real” objects⁹ as “Platonic information” and applying aspects of QIT to Platonic information enables us to close the connectivity gap between the Platonic realm and the physical universe.

This approach allows us to:

- Platonically reinterpret QIT explanations of nonlocal physical phenomena such as quantum entanglement (and reintroducing “hidden variables” as Platonic information).
- Suggest possible areas for subsequent Platonic studies (relative Platonic quantification, propose methods for determining comparative “sizes” of different sets of Platonic information possibly drawing parallels with Cantor’s infinities, and so on.).

Borrowing widely accepted concepts from Quantum Information Theory (QIT) as Susskind did from information theory, we can restate the “hidden variables-guiding equation” explanatory feature of Bohmian mechanics in Platonic terms.¹⁰

⁹ This thesis conflates mathematically “real objects” and “Platonic forms” together.

¹⁰ This interpretation of Platonic entities as “information” may meet the criteria set by Mark Balaguer. He argues that *belief in real objects is justified if one could explain how they might exist*. See the review of Balaguer position in Mary Leng, “Mark Balaguer, Platonism and Anti-Platonism,” *Bulletin of Symbolic Logic*, 8.4 (2002), 516-518.

Part One: Quantum Nonlocality

Overview

This part broadly traces the history of quantum nonlocality theory. It summarizes the background of action-at-a-distance in physics, describes the emergence of quantum nonlocality as an aspect of orthodox quantum theory, discusses the Einstein-Podolsky-Rosen paper questioning the completeness of quantum mechanics, and explains the role of hidden variables in Bohmian mechanics.

Next, Bell's Inequalities, probabilistically establishing the necessity for quantum nonlocality, is discussed. Then, this part discusses nonlocality after Bell, describing experimental verifications, the relationship of quantum nonlocality and property theory, and identifies several non-hidden variable explanations of nonlocality.

After discussing the basic elements of Bohmian mechanical hidden variables and other explanations of quantum nonlocality, this part identifies the minimum requirements that must be met for an adequate interpretation of hidden variables as something else (e.g., Platonic entities). Finally, this part introduces quantum information theory and the related field of entanglement-dependent quantum computing.

Locality and Nonlocality

In classical (pre-QM) physics, "locality" referred to the contiguity of objects or systems. One thing affected another by exerting force or sending something (for example, a signal) to another. Nonlocality refers to action-at-a-distance or the transfer of influence (such as a repulsive or attractive force) without a method or media of transfer.

Physics has struggled with nonlocality for centuries. In its current guise, quantum

entanglement poses fundamental questions. Several contemporary philosophers, physicists, and mathematicians suggest that quantum nonlocality requires us to revise many of our basic notions. For example, Richard Healey (Philosophy Department, University of Arizona) finds that the individual members of “coupled” or entangled system are fundamentally changed by their interaction, “when two systems, of which we know the [individual] states by their respective representatives, enter into temporary physical interaction due to known forces between them, and when after a time of mutual influence the systems separate ... then they can no longer be described the same way ... by endowing each ... with a representation of its own ... this [shared, nonlocal condition is] *the* characteristic of quantum mechanics.”¹¹

After discussing its background, this section introduces the current explanations for quantum nonlocality.

Background

In western science, the philosophical problem of action-at-a-distance or nonlocality is at least four hundred years old. In the 17th century, Newton had introduced nonlocal action at a distance by suggesting that gravity is exerted between masses according to an inverse square law¹² instantaneously at any distance.¹³ This non-

¹¹ Richard Healey, *The Philosophy of Quantum Mechanics: An Interactive Interpretation*, (Cambridge: Cambridge University Press, 1989), 187.

¹² Roger Penrose, *The Road to Reality, A Complete Guide to the Laws of the Universe* (New York: Alfred A. Knopf, 2005), 390.

¹³ Yet Newton was philosophically opposed to action-at-a-distance. Karl Popper quotes a Newton letter, “that one body may act upon another at a distance...is to me so great an absurdity that...no man who has

contiguous connection was needed to make his formulation consistent with Kepler's discovery that planetary angular momentum is conserved.¹⁴ Almost two hundred years later, studying rotational motion, Mach restated the problem, hypothesizing that each particle in the universe is instantaneously affected by every other particle. In 1916, Einstein sought to remove action-at-a-distance in General Relativity (GR). In that formulation, local effects expressed as gravity (space-time curvature) were propagated at the speed of light. But the statistical nature of quantum mechanics required the reemergence of nonlocality.¹⁵

Probabilistic Quantum Mechanics and Emergent Nonlocality

In the 20th century, nonlocality appeared as a necessary corollary of the probabilistic nature of quantum mechanics.¹⁶ This section briefly summarizes its emergence.

In 1925, Erwin Schrödinger introduced a partial differential wave equation that

in philosophical matters a competent faculty of thinking can ever fall into it.” Karl Popper, *The World of Parmenides, Essays on the Presocratic Enlightenment* (New York: Routledge, 1998), 204.

¹⁴ Penrose, *The Road to Reality, A Complete Guide to the Laws of the Universe*, 686.

¹⁵ Brian Greene notes the role of apparent action-at-a-distance in our concepts of separating space, “Results from theoretical and experimental considerations strongly support the conclusion that the universe admits interconnections that are not local ... space cannot be thought of as ... intervening space, regardless of how much there is, does not ensure that two objects are separate, since quantum mechanics allows an entanglement, a kind of connection, to exist between them.” Brian Greene, *The Fabric of the Cosmos* (New York: Vintage Books, 2005), 80.

described the energy states of matter. His wave equations were centrally significant in subsequent advances in quantum theory.

Schrodinger's equation describes the evolution of the changing state of a particle through time. The state of a system at time t_0 determines its expression at future times.¹⁷ Multiple instances of this equation may be superimposed, resulting in an entangled condition. Sets of equations may be summed (wave function) and separated when the particle-waves described by the equations move apart. Although the separating distance may be light years (across a galaxy), the wave function continues as a superimposed/entangled system.¹⁸

Schrodinger realized that his formulation contradicted our conception of particles as persistent objects. "The elementary particle is not an individual; it cannot be

¹⁶ "Quantum mechanics can be regarded as a non-classical probability calculus resting upon a non-classical propositional logic ... in quantum mechanics each probability-bearing proposition of the form "the value of physical quantity A lies in the range B " is represented by a projection operator on a Hilbert space H . These form a non-Boolean ... non-distributive, orthocomplemented lattice. Quantum-mechanical states correspond exactly to probability measures (suitably defined) on this lattice." Alexander Wilce, "Quantum Logic and Probability Theory", *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, (Stanford: Metaphysics Research Lab, 2009), <http://plato.stanford.edu/archives/spr2009/entries/qt-quantlog/> (accessed September 27, 2008)

¹⁷ The standard form of the equation is: $\delta^2\psi/\delta x^2 + 8\pi^2m/h^2 (E-V)\psi = 0$ where δ^2 is the second derivative with respect to X , Ψ is the wave function, h is Planck's constant, m the particle mass, E the total energy, and U the potential energy. See Dan Summons, "What is the Schrodinger Equation?" <http://www.physlink.com/Education/AskExperts/ae329.cfm?CFID=22564684&CFTOKEN=14110569> (accessed September 14, 2008)

¹⁸ The solution to a superimposed (entangled) state may be represented as: " $\Psi = C_1 \Psi_1(x,t) + C_2 \Psi_2(x,t) + \dots + C_n \Psi_n(x,t) = \sum C_i \Psi_i(x,t)$. When a particle is subject to a time-independent potential $V(x)$, solutions to the Schrödinger equation[s] can be found [by separating] variables." David McMahon, *Quantum Mechanics DeMystified, A Self Teaching Guide* (New York: McGraw-Hill, 2006), 16, 35. Also, see Penrose, *The Road to Reality, A Complete Guide to the Laws of the Universe*, 516–17. The expression indicating the new solution, reflecting the separation is $\Psi(x,t) = \Phi(x)f(t)$. Because the potential is "time-independent," the solution continues as separating particles move apart across light years of distance.

identified, it lacks sameness.... The implication ... is that the unsuspected epithet 'this' is not quite properly applicable to, say, an electron, except with caution, in a restricted sense, and sometimes not at all."¹⁹ Some theorists would continue to seek a persisting reality at the quantum level²⁰ but most concurred with Schrodinger's observation.

According to Roger Penrose, the Schrödinger equations lead directly to entanglement mysteries. The "Schrödinger evolution [predictable values of a particle from time t_0 forward] will usually ... plunge us into the depths of entanglement and will not provide us with any route ... out of this enormous seaweed-strewn ocean of entangled states ... these entanglements are everywhere around us, the question is 'Why do these ubiquitous effects not confront us at every turn?'"²¹

In 1927, Max Born reemphasized the probabilistic nature of QM. He argued that the Schrödinger equation did not represent an electron (or other particle) as spread out over an area of space, but was instead a probabilistic estimate of its location.

¹⁹ Ewin Schrodinger, "What Is an Elementary Particle" in *Interpreting Bodies*, ed. E. Castelani, 197-210 (Princeton: Princeton University Press, 1998).

²⁰ Christian de Ronde argues that shifting our interpretation from focusing on entities to defining faculties of observation enables us to portray wave functions as representing reality. "The orthodox interpretation presents the superposition as ... the electron itself ... the probability of finding a particular property of this entity ... within this interpretation the superposition encodes the properties of a system. Our interpretation in terms of faculties presents the superposition as referring to a certain faculty, which I have in relation to the experimental arrangement ... encoded in a mathematical expression.... Observation takes place through the shift of energy within a given state of affairs. Objectivity is regained in quantum measurements when we forget about entities and discuss in terms of faculties. Just like entities exist even when there is no light to see them, faculties exist in the world regardless of observation and measurement outcomes." Christian de Ronde, "Interpreting The Quantum Wave Function in Terms of 'Interacting Faculties'," in *PhliSci Archives*, (December 2007), <http://philsci-archive.pitt.edu/archive/00003691/> (accessed September 14, 2008)

²¹ Penrose, *The Road to Reality, A Complete Guide to the Laws of the Universe*, 591-592. A typical QM answer to Penrose's question would be that we cannot distinguish the cumulative result of thousands of quantum-level entanglements collapsing each second as macroscopic events. Do we hear echoes of Heraclitus and Parmenides still arguing?

In the 1930's quantum theory was in flux with the leading wide-ranging positions advocated by John von Neumann's axiomatization (QM phenomena as linear operators in Hilbert space) and Paul Dirac's equations for the motion of a wave function and wave-particle duality.²² In a 1932 paper, von Neumann found that a "wave function collapse"²³ was implied by quantum theory and that hidden variables were unnecessary. A probabilistic, nonlocal change occurred when a measurement was made. From an observer's perspective, the collapse is instantaneous (faster than the speed of light). In this paper, von Neumann "proved" that "hidden variables" such as those proposed by

²² "[In the 1930s] QM found itself in a ... crisis. On the one hand, its apparent non-determinism had not been reduced to an explanation of a deterministic form. On the other, there still existed two independent but equivalent heuristic formulations ... matrix mechanical formulation [of] Werner Heisenberg and the wave mechanical formulation [of] Erwin Schrodinger, but there was not yet a single ... theoretical formulation. After ... axiomatiz[ing] set theory, von Neumann [turned to] axiomatization of QM. He realized, in 1926, that a quantum system could be considered as a point in a ... Hilbert space, analogous to ... 6N dimension (N is the number of particles, 3 general coordinate and 3 canonical momenta for each coordinate). The *physics* of quantum mechanics was thereby reduced to the *mathematics* of the linear Hermitian operators on Hilbert spaces. For example, the uncertainty principle of Heisenberg, according to which the determination of the position of a particle prevents the determination of its momentum and vice versa, is translated into the *non-commutativity* of the two corresponding operators. This new mathematical formulation included as special cases the formulations of both Heisenberg and Schrödinger, and culminated in ... 1932 [publication]. However, physicists ... prefer[ed] another approach ... formulated in 1930 by Paul Dirac. Von Neumann's abstract treatment permitted him also to confront the foundational issue of determinism vs. non-determinism ... he demonstrated a theorem according to which quantum mechanics could not possibly be derived by statistical approximation from a deterministic theory of the type used in classical mechanics. This demonstration contained a conceptual error, but it [lead to] the work of John Stuart Bell in 1964 on Bell's Theorem and the experiments of Alain Aspect in 1982 [which] demonstrated that quantum physics requires a notion of reality substantially different from that of classical physics." Wikimedia Foundation, Inc. "John Von Neumann," (2008), http://en.wikipedia.org/wiki/Von_Neumann#Quantum_mechanics (accessed July 19, 2008)

²³ The wave function (also known as the "wavefunction") is a mathematical "function $\psi(x,y,z)$ appearing in the Schrodinger equation...involving the coordinates of a particle in space. If the Schrodinger equation can be solved for a particle in a given system ... depending on the boundary conditions, the solution is a set of allowed wave functions (eigenfunctions) of the particle, each corresponding to an allowed energy level (eigenvalue). The *physical significance of the wave function is that the square of its absolute value, $|\psi|^2$, at a point is proportional to the probability of finding the particle in a small volume, $dxdydz$, at that point* [my italics]." John Daintith and Elizabeth Martin, eds. *Oxford Dictionary of Science* (Oxford: Oxford University Press, 2005), 865.

deBroglie were impossible. Subsequent work demonstrated that von Neumann was wrong.²⁴

Later, a von Neumann thought experiment led to the extension of the entropy concept from thermodynamics to quantum mechanics (QM). Postulating “von Neumann’s entropy,” he suggested a new way to determine the “capacity of a communications channel.” Soon his idea was applied to interpreting outcome measurements of entangled systems.²⁵

Although QM is the widely accepted probabilistic view of the world, some theorists continue to wonder if we could describe reality more concretely.²⁶ Recently, Christian de Ronde (Center Leo Apostel and Foundations of the Exact Sciences, Brussels Free University) argued, somewhat phenomenologically, that we can interpret quantum wave functions as descriptive of the physical world if we shift our perspective from “entities” of observation to observing “faculties.”²⁷

The next section introduces the paper that lead to predictions of nonlocality.

²⁴ Lee Smolin, *Three Roads to Quantum Gravity*. (New York: Basic Books, 2001), 323, 369.

²⁵ “The critical behavior of entanglement near a quantum phase transition has been studied intensely over the past few years.... Using finite size scaling methods we calculate the critical charge and the critical exponent associated to the von Neumann entropy. The parallelism between the behavior of entanglement near a quantum phase transition and the behavior of the von Neumann entropy in a critical few-body quantum system is analyzed.” Omar Osenda and Pablo Serra in *Physical Review Letters A* 75. 042331 (2007) <http://link.aps.org/doi/10.1103/PhysRevA.75.042331> (accessed September 14, 2008)

²⁶ Smolin, *Three Roads to Quantum Gravity*, 323.

²⁷ Christian de Ronde, “Interpreting The Quantum Wave Function in Terms of ‘Interacting Faculties’,” in *PhliSci Archives*, (December 2007), <http://philsci-archive.pitt.edu/archive/00003691/> (accessed September 14, 2008)

Einstein, Podolsky, and Rosen Paper

In 1935, Albert Einstein, Boris Podolsky, and Nathan Rosen (EPR) published a paper²⁸ that attempted to show the incompleteness of QM. They based their conclusion on three points: 1) correctness of statistical predictions of QM, 2) reality of the physical world, and 3) an “assumption of locality.”²⁹

Something else was needed (Bohm’s later “hidden variables”), they argued, to complete quantum theory. Without additional factors, the paper showed that the quantum “world is ... indeterministic and prior to measurement, the physical system measured does not possess determinate properties corresponding to the measurement outcomes.”³⁰ And, nonlocal action-at-a-distance, theoretically made obsolete by SR and GR, was again part of physics.

As the EPR noted, when a pair of “entangled” particles (known as a “singlette”) is

²⁸ Albert Einstein, Boris Podolsky, and Nathan Rosen, “Can Quantum Mechanical Description of Physical Reality Be Considered Complete?” *Physical Review* 47 (May 1935), 770-780.

²⁹ Amir D. Aczel, *Entanglement* (New York: Penguin Books, Ltd., 2003), 152.

³⁰ The EPR paper “considered a system of two spatially separated particles, A and B, in a particular quantum state, Ψ . Ψ does not determine the results of measuring the positions of A and B but, given the results obtained on measuring A’s position, it does allow one to predict B’s position with certainty. It therefore seems that B has a determinate position immediately after A’s position is measured [but not before]... Because A and B are spatially separated, B’s position cannot be [determined] as a result of the measurement of A’s position with Some sort of ‘action at a distance.’ ...to uphold a principle of locality [no action at a distance], EPR conclude[d] that B must have had a determinate position all along and that QM is thus incomplete. However, Bell’s theorem [later] show[ed] that regarding QM as incomplete is not sufficient to save locality.” *The Oxford Companion to Philosophy, Second Edition*, ed. Ted Honderich, 237 (Oxford: Oxford University Press, 2005).

created and separates, parallel features (for example, particle spin³¹) of the individual particles are “correlated.”³² Their apparently nonlocal connection continues as the particles travel apart. When a correlated feature (for example, spin up) of one is detected, the probability of a specific correlated value for that state (for example, spin down) in the other particle, possibly light years away, is high before measurement. The Copenhagen interpretation of QM accepts this event as a result of instantaneous wave collapse.

EPR explains these correlations (and transferred information) as the result of as-yet unknown properties of the particle-wave system. These theoretical entities, they argued, must be local.³³ No instantaneous action-at-a-distance is necessary. Bohr, Heisenberg and others, strictly upholding the Copenhagen Interpretation, accepted the existence of nonlocal entanglement but rejected the need for any “hidden variables.” Instead, they labeled the possibility of particle entanglement as “mystery z” of quantum mechanics. In the succeeding years, experiments proved them right. Nonlocality had a

³¹ In QM, spin has two components: rotational speed and the direction (“up” or “down”) of the spin axis; together, these are expressed as a vector (speed in a direction). In a wave function, particle spin is defined as up or down states. In the EPR thought experiment, two particles (one with up spin, the other with down spin) were created together, then separated. According to QM, if you determine the spin direction of one, you immediately know what the spin of the other will be if it’s measured. EPR sought to show that because of this complementarity, each of the separating particles must have a specific spin direction, not merely a probability of spin direction. But QM only allows a probability of finding the correct spin. EPR suggests that something’s missing: hidden variables.

³² For example, when a laser beam strikes a cesium atom, the system raises higher energy level and quickly drops back down again, emitting energy as two entangled photons moving in exactly opposite directions. See the description of Aspect’s test for entanglement in “Quantum Nonlocality Experimentally Verified,” below.

³³ EPR predicted the entanglement of particles that share the same wave function. Experimentally, two or three particles can be created together sharing one wave function, separate them, influence one with an outside input (e.g., changing the spin), and later compare the separated quantum states. One will depend upon the others. EPR argued that a causal agent must be missing for this nonlocality event to occur. How could a change on one particle instantly affect the state of a physically separated particle? They concluded that QM was incomplete because something else was needed to explain the transfer of information.

role in physics.

Bohmian Mechanics and Hidden Variables

In 1951, David Bohm, studying at Princeton, was convinced by conversations with Einstein that QM was incomplete. Bohm proposed that “hidden variables”³⁴ were needed to justify some of the predictions (including nonlocality) of QM. For example, the decay time of a radiating system is fixed, not random. However, the determining variable(s) are hidden. In the Bohemian Mechanics (BM) interpretation of QM, particles maintain a specific position and velocity but they cannot be detected. Any measurement destroys the pilot wave (and information) associated with the particle.³⁵

Bohm hoped to avoid the apparently causality-breaking conditions suggested by EPR and nonlocality. In many ways, equivalent to quantum mechanics, Bohm’s theory predicts the same outcomes of measures as QM. As others have noted, Bohm resurrected deBroglie’s earlier argument for “hidden variables,” putting it on firmer mathematical foundations.³⁶

BM defines the “physical state of a particle system [in terms of] a vector in ...

³⁴ “Local hidden variables theories ... attempt to eliminate the stochastic [statistical-probabilistic] element of quantum theory by adding extra parameters to the usual quantum formalism, parameters whose values determine the results of the experiments.” Tim Maudlin, *Quantum Nonlocality and Relativity*, Second Edition (Oxford: Blackwell Publishers, 2002), 19.

³⁵ Penrose, *The Road to Reality, A Complete Guide to the Laws of the Universe*, 585–589.

³⁶ Smolin, *Three Roads to Quantum Gravity*, 323.

Hilbert space³⁷ (agree[ing] with QM) and the [unlike QM] positions of the particles at t ... electrons (and other particles) always possess definite positions and have determinate trajectories.... The evolution of the mathematical quantum state is governed by the Schrodinger equation and the evolution of particle positions is governed by a ‘guidance equation.’”³⁸

Restating Schrödinger’s wave equation, Bohemian mechanics gives a new interpretation to wave-particle duality. In the original quantum mechanical view, waves only represented potentiality. A particle “appeared” when it was measured. Bohm dropped the idea of wave potentiality. In his mechanics, both the particle and wave are physically real. The wave guides the particle through a “quantum force” created by a “quantum potential.” A particle is physically real at all times, following a course determined by the quantum potential. According to Bohm, this approach enabled causality. He argued that Heisenberg’s Uncertainty Relations only explained epistemological limits to human knowledge, not the ontological, physical states of

³⁷John von Neumann worked toward formalizing quantum theory by applying David Hilbert’s concept of space to the mathematical formulations of Bohr, Heisenberg, and Schrodinger. In von Neumann’s scheme (and those who followed him), a multidimensional Hilbert space could contain all possible configurations of a quantum system. Understandable as an extension of ZFC set theory, Hilbert space generalizes “finite-dimensional vector spaces to include vector spaces with infinite dimensions...provid[ing] a foundation of quantum mechanics, and there is a strong physical and philosophical motivation to study its properties. For example, the properties of Hilbert space ultimately determine what kinds of operations are theoretically possible in quantum computation.” Norman Megill, “Hilbert Space Explorer Home Page,” (December 2007), <http://us.metamath.org/mpegif/mmhil.html> (accessed April 5, 2008)

³⁸Barry Loewer, “Copenhagen versus Bohemian Interpretations of Quantum Theory,” *The British Journal for The Philosophy of Science* 49, no. 2 (June 1998), <http://bjps.oxfordjournals.org/cgi/reprint/49/2/317> (accessed April 5, 2008)

particles.³⁹ Bohm held that a particle had equally definite position and momentum.

However, we cannot know them simultaneously because they are determined by the “guiding equation.”⁴⁰ Bohm argued that the classic two-slit experiment should be reinterpreted. When a particle moves through the setup, the slit through which it passes and the place where it “hits” the target are completely determined by its initial position and wave function.

Tim Maudlin (Philosophy Department, Rutgers University)⁴¹ agrees that Bohmian mechanics is deterministic.⁴² Unlike the position of orthodox quantum theory, “the wave

³⁹ Although it was not originally presented as an epistemological theory, Heisenberg’s uncertainty formulation is now interpreted as a statement of the limits to our knowledge. See Jan Hilgevoord and Jos Uffink, “The Uncertainty Principle,” *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, (Stanford: Metaphysics Research Lab, 2008), <http://plato.stanford.edu/archives/fall2008/entries/qt-uncertainty/> (accessed August 16, 2008)

⁴⁰ Latter, the “guidance equation” became commonly known as the bohemian mechanical “hidden variable.”

⁴¹ In another recently published work, Maudlin proposes a new metaphysics based on contemporary physics. He “advocates the view that laws of nature should be taken as primitive and ...uses them ...to analyze many counterfactual [arguments] and to ground the fundamental dynamical explanations so prized in science. He defends ...his view over rival proposals of David Lewis and Bas Van Fraassen, among others. Maudlin [argues that their elimination of intuition in scientific reasoning] deprives [us of] one [way] to say how cutting down its class of models can enhance a theory’s explanatory power.” Richard Healey, “Tim Maudlin, *The Metaphysics Within Physics*” in *Notre Dame Philosophical Reviews* (February 2008), <http://ndpr.nd.edu/review.cfm?id=12283> (accessed March 29, 2008)

⁴² “The wave function always develops accord[ing to] Schrodinger’s equation ... [with] no wave collapse.” “The dynamics is deterministic... [T]he ‘hidden’ parameters also evolve deterministically.... In Bohmian particle mechanics ... like classical mechanics particles ... have definite position and trajectories... Schrodinger’s cat problem cannot arise for Bohm ... In addition to particles, Bohm’s theory recognizes a real physical object ... described by the wave-function. This object [is] ... wave-function of the system ... not made up of particles ... [it] evolves accord[ing to] Schrodinger’s equation ... it determines how the particles will move. Bohm’s theory...consists in two equations. Schrodinger’s equation [that] determines how the wave-function changes [and an equation that] specifies how the particle positions will change given the wave-function ... the physical state of the system is specifi[ed] by ... both the wave-function ... and positions of its particles ... the two equations determine how the system will evolve. Bohm’s equation (also known as the “guiding equation”) is: ‘ $dq/dt = \hbar \text{Im grad} \psi / \psi(q)$ ’ where $q = (q_1, \dots, q_N)$ specifies the position of particles 1 through N, ψ is the wave-function, and V is the potential energy of the system ... the wave-function directly determines the velocities of the particles.” Tim Maudlin, *Quantum Nonlocality and*

function is not complete. [In addition to] the physical factors reflected in the wave function, a system has other physical properties. [P]articles always have definite positions [and] fields always have definite values ... two systems can have identical wave-functions but be in different physical states since the values of these other properties may differ. These extra physical parameters which are not reflected in the wave-function are commonly (and misleadingly) called ‘hidden variables.’”⁴³

The deterministic nature of Bohm’s formulation does away with the measurement problem because each physical state of a particle is always determined. In Bohm’s system a wave function collapse is explained as a “conditional wave function of a subsystem ... configuration” evolving according to Bohm’s “guiding equation.” Traditional quantum mechanics has not provided as clear a description of wave collapse.⁴⁴

Like orthodox QM, Bohmian mechanics is in many respects, nonlocal. The “guiding equation” or “hidden variables” supplies information shared by entangled particles. A change in any state (for example “up spin”) of one particle of an entangled pair is immediately made in the corresponding state of the other (for example, “down spin”).⁴⁵

Relativity (Oxford: Oxford University Press, 2007), 117-119.

⁴³ Ibid, 117.

⁴⁴ Sheldon Goldstein, “Bohmian Mechanics,” *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, (Stanford: Metaphysics Research Lab, 2006), <http://Plato.stanford.edu/entries/qm-bohm/> (accessed August 16 , 2008)

⁴⁵ “The velocity, as expressed in guiding equation, of any one of the particles of a many-particle system will typically depend upon the positions of the other, possibly distant, particles whenever the wave function

Bell's Inequalities Theorem

In two remarkable papers (1964 and 1966),⁴⁶ John Bell showed that no physical theory of local hidden variables⁴⁷ could produce the results of quantum mechanics.⁴⁸ He proved that the probabilities of measurement results were limited by locality according to “Bell’s inequalities.” Using test-results-probability expressions, Bell showed that either QM must be reconciled with nonlocality (not necessarily contravening SR⁴⁹) or the objective reality of particle properties (e.g., quantum states⁵⁰) had to be denied.⁵¹ Modifying the EPR thought experiment, Bell proposed a two measurement experiment of a pair of distant, entangled particles. The first would test predictions of “quantum

of the system is entangled, i.e., not a product of single-particle wave functions. This is true, for example, for the EPR-Bohm wave function, describing a pair of spin-1/2 particles in the singlet state, analyzed by Bell and many others. Thus does Bohmian mechanics make explicit thefeature of quantum theory: quantum nonlocality.” Ibid.

⁴⁶ John Bell, “On the Einstein Podolsky Rosen Paradox,” *Physics*, 1, no. 3 (1964) and “On the problem of hidden variables in quantum mechanics,” *Reviews of Modern Physics*, 38.3 (July 1966).

⁴⁷ However, Bell did not rule out nonlocal hidden variables.

⁴⁸ “Bell’s theorem is a mathematical result aimed at showing that the explanation of the statistical correlations that hold between causally non-interactive systems cannot always rely on the positing that when the systems did causally interact in the past independent values were fixed for some feature of each of the two systems that determined their future observational behaviour. The existence of such ‘local hidden variables’ would contradict the correlational predictions of quantum mechanics. The result shows that quantum mechanics has a profoundly ‘nonlocal’ nature.” *The Cambridge Dictionary of Philosophy*, Second Edition, ed. Robert Audi (Cambridge: Cambridge University Press, 1999), 703.

⁴⁹ Although Bell’s theory upholds nonlocality in QM, it does not invalidate Special Relativity. A no-communications theorem corollary indicates that observers cannot use the inequality violations to communicate information to each other at faster-than-light speed. Penrose, *The Road to Reality, A Complete Guide to the Laws of the Universe*, 282, 803.

⁵⁰ “[A quantum state is] the state of a quantized system as described by its quantum numbers. For instance, the state of a hydrogen atom is described by the four quantum numbers n , l , m_l , [and] m_s . In the ground state they have values 1, 0, 0, and $\frac{1}{2}$, respectively.” *Oxford Dictionary of Science* eds. John Daintith and Elizabeth Martin (Oxford: Oxford University Press, 2005), 680.

⁵¹ Penrose, *The Road to Reality, A Complete Guide to the Laws of the Universe*, 583–586.

theory,” the second would test “local reality” predictions, espoused by the EPR paper. In Bell’s scheme (actually a set of probability statements), after the first experiment, the detection angle of measuring devices would be changed and a new measurement would be taken in less time than a light speed signal could pass between the two entangled particles. Each measuring observer would independently determine the spin of her/his particle. Finally, according to Bell, quantum nonlocality must exist and superluminal communication is impossible while “superluminal causation” is necessary.⁵² Bell’s predictions were so explicit⁵³ that they were later tested and verified. Although his theory has been interpreted that way, *Bell did not totally dismiss “hidden variables.”*⁵⁴ His inequalities demonstrate that “local” hidden variables contradict predictions of QM.

⁵² Quantum nonlocality must exist because “violations of Bell’s inequality predicted by quantum theory do not allow superluminal signals to be sent...inequalities cannot be violated by any theory in which all of the causes of an event lie in its past ... [although] nature may not allow superluminal signalling, it does employ, according to Bell, superluminal causation.” Maudlin, *Quantum Nonlocality and Relativity*, 116.

⁵³ In Bell’s formulation, “ P_a is the probability that a particular spin is detected by detector A [on the left], P_b is the corresponding probability for the right-hand detector. Neither P_a nor P_b can be larger than +1 or smaller than -1 ... the Bell inequality [is defined by] a new expression... [Given] the correlation between the two detectors, $P(\alpha, \Phi)$ is the probability that a particle [is] registered at detector A, at angle α ... at the same time, its companion [entangled] is registered at B, at angle Φ Bell [derived] the following relationship between the various probabilities. Its derivation [does not depend] upon the physical details of the detectors.... Given that all the probabilities lie between -1 and +1, Bell showed that $P(\alpha, \Phi) - P(\alpha, \Phi') + P(\alpha', \Phi) + P(\alpha', \Phi') - P_a(\alpha) - P_b(\Phi) \leq 0$ [Which can be rewritten as:] $-2 \leq P(\alpha, \Phi) - P(\alpha, \Phi') + P(\alpha', \Phi) + P(\alpha', \Phi') \leq 2$. Writing the central term as $F_{\text{local reality}}$, Bell’s expression becomes: $-2 \leq F_{\text{local reality}} \leq 2$. The formula for the quantum mechanical case ... [is complex] and has to be worked out for each particular value of the angles α and Φ . Unlike the local reality case, it is not separable into a product of location contributions from ... detectors A and B. It is a fully nonlocal expression. For example, [with] detectors oriented at angles of 45 deg $F_{\text{quantum theory}} = 2.83$, a number that exceeds the upper limit of +2 demanded by any local reality theory.” F. David Peat, *Einstein’s Moon, Bell’s Theorem and the Curious Quest for Quantum Reality* (Chicago: Contemporary Books, 1990), 110-112.

⁵⁴ “It has been argued that quantum mechanics is not locally causal and cannot be embedded in a locally causal theory. That conclusion depends on treating certain experimental parameters, typically the orientations of polarization filters as free variables. But it might be that this apparent freedom is illusory. Perhaps experimental parameters and experimental results are both consequences or partially so of some hidden mechanism. Then the apparent nonlocality could be simulated.” John Bell, “Free Variables and Local Causality,” *Epistemological Letters*, 15 (1977). 112.

A few years later he argued that De Broglie and Bohm's "pilot wave" interpretation of nonlocal "hidden variables" was reasonable.⁵⁵ Later, Bell continued his work, affirming that that causality at the quantum level must be nonlocal.⁵⁶

This thesis accepts Bell's proof, arguing that Platonic, nonlocal hidden variables may account for the results of entanglement.

Quantum Nonlocality After Bell

After Bell's work establishing the necessity of quantum nonlocality, it was experimentally verified and research continued into the ramifications of nonlocality. Years after Bell demonstrated the need for quantum nonlocality, theoreticians continued to ask about a relationship between the structures described by quantum mechanics and

⁵⁵“In 1952 I saw ...papers by David Bohm show[ing] ... how parameters could be introduced into nonrelativistic wave mechanics, with the help of which the indeterministic description could be transformed into a deterministic one ... subjectivity of the orthodox version ... could be eliminated . the idea had been advanced already by de Broglie in 1927, in his 'pilot wave' picture. But why ... had Born not told me of this 'pilot wave'? Why did von Neumann not consider it? More extraordinarily, why did people go on producing 'impossibility' proofs [against hidden variables] after 1952, and as recently as 1978? ... Why is the pilot wave picture ignored in text books? [It shows] that vagueness ... and indeterminism are not forced on us by experimental facts but by deliberate theoretical choice. The de Broglie – Bohm theory ... was the explicit representation of quantum nonlocality ... [It] disposes of the necessity to divide the world ... into system and apparatus. But another problem is ... [that] any sharp formulation of quantum mechanics has a very surprising feature: the consequences of events at one place propagate to other places faster than light. This happens in a way that we cannot use for signaling. Nevertheless it is a gross violation of relativistic causality.... The specific quantum phenomena that require such superluminal explanation have been ... realized in the laboratory ... by Aspect, Dalibard, and Roger, in Paris in 1982. [T]his is the real problem with quantum theory: the ... conflict between any sharp formulation and fundamental relativity ... a real synthesis of quantum and relativity theories [may] require not just technical developments but radical conceptual renewal.” John Bell, *Speakable and Unsayable in Quantum Mechanics*, (Cambridge: Cambridge University Press, 1987), 160, 166, 171-172.

⁵⁶ “Quantum mechanics is not locally causal and cannot be embedded in a local causal theory. That conclusion depends on treating certain experimental parameters, typically the orientations of polarization filters, as free variables... [I can restate my earlier argument so that the variables are treated]... 'at least effectively free for the purpose at hand.'... [using a random generator, so that]... the output of such a device [randomiser] is indeed a sufficiently free variable... and the theorem [quantum mechanics is not locally causal] follows.” Ibid, 100-103.

local reality. For example, Marek Zukowski (Institute for Theoretical Physics, Gdansk) and Caslav Brukner (Institute for Experimental Physics, Vienna) notes, “No local realistic theory agrees with all predictions of quantum mechanics as quantitatively expressed by violation of Bell's inequalities. Local realism ... is based on everyday experience and classical physics ... [and] supposes that measurement results are predetermined by the properties the particles carry *prior to and independent of* observations. Locality supposes that these results are independent of any action at space-like separations.”⁵⁷

After Bell, quantum nonlocality was the practical basis for quantum computing and quantum cryptography. These developments are introduced in the later section “Quantum Information, Computing, and Cryptography.”

Kochen-Specker Dismiss Bohmian Hidden Variables

In 1967, Simon Kochen and Ernst Specker developed a strong position against Bohmian and similar hidden variable arguments for interpreting quantum mechanics as deterministic. Accepting Bell's observation that von Neumann's approach to discounting hidden variables was flawed, they sought to provide a conclusive “proof of the nonexistence of hidden variables.” Kochen and Specker showed that the apparently QM equivalent statistical results of Bohmian hidden variables “do not take into account the algebraic structure of quantum observables. A minimum such structure is given by the

⁵⁷ Marek Zukowski and Caslav Brukner, “Bell's Theorem for General N-Qubit states,” in *Physical Review Letters*, 88.210401 (2002), http://xxx.sissa.it/PS_cache/quant-ph/pdf/0102/0102039v3.pdf (accessed April 12, 2008)

fact that some observables are functions of others. This [non-commutative⁵⁸] structure is independent of the particular theory under consideration and should be preserved in a classical reinterpretation.”⁵⁹ Kochen-Specker advanced the position that QM mathematics represented probabilities instead of physical reality. “The Kochen-Specker proof demonstrates the impossibility of Einstein's assumption, made in the famous Einstein-Podolsky-Rosen paper, that quantum mechanical observables represent ‘elements of physical reality’. More generally does the theorem exclude hidden variable theories requiring elements of physical reality to be noncontextual (i.e. independent of the measurement arrangement).”⁶⁰

Quantum Nonlocality Experimentally Verified

In 1982, Alain Aspect and co-workers at the Institut d'Optique in Paris verified Bell's theory of inequalities. A pair of photons created as a single decay event was emitted by the source. They traveled in opposite directions for a distance until they hit variable polarizers, the results of their interaction with the polarizers was recorded at each end. When the outcome was analyzed, the results verified quantum mechanics

⁵⁸ The restrictions imposed by the Uncertainty Relations are partially met by using non-commutative algebra (for example, $XY \neq YX$) in QM.

⁵⁹ Simon Kochen, E. Specker, “The Problem of Hidden Variables in Quantum Mechanics,” in *Indiana University Mathematics Journal*, 17.1 (1968).
<http://www.iujm.indiana.edu/IUMJ/dfulltext.php?year=1968&volume=17&artid=17004> (accessed April 12, 2008)

⁶⁰ Carsten Held, “The Kochen-Specker Theorem,” *The Stanford Encyclopedia of Philosophy*, *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, (Stanford: Metaphysics Research Lab, 2006),
<http://Plato.stanford.edu/entries/kochen-specker> (accessed April 13, 2008)

nonlocality and showed a correlation that could not be supported by hidden variables.⁶¹

The Paris test results were noticed worldwide. A few months later, writing in *Science* magazine, University of Washington physicist John Cramer noted among “physicists who concern themselves with this dilemma ... the prevailing view seems to be that one must give up ‘realism,’ since the alternative of allowing nonlocality leads to unacceptable conflicts with causality and special relativity.”⁶² However, Cramer personally felt that he could “retain realism” by appealing to the classical Copenhagen Interpretation of Bohr that the mathematics of quantum mechanics was only the best attempt at describing the quantum level world.⁶³ Cramer would put aside the inexplicably inconvenient, nonlocal results of Aspect’s experiment. But the test had shown something physically real.

A few years later (1986), Ghirardi, Rimini, and Weber (GRW)⁶⁴ proposed a solution to the collapse and nonlocality problem by changing quantum mechanics. Their approach allows the quantum state of a quantum system to develop according to Schrödinger’s equation. At random instants, development stops and the quantum state spontaneously collapses into a single local state. But like Bohm’s formulation, GRW assumes instantaneity. Random collapses occurs faster superluminally, violating Special

⁶¹ Alain Aspect, Jean Dalibard, and Gnaud Roger. “Experimental Test of Bell's Inequalities Using Time Varying Analyzers.” *Physical Review Letters* 49 (1982), 1804–1807.

⁶² “[The] Copenhagen interpretation dealt with these problems by asserting that the quantum mechanical state vector describing a given system is only a mathematical representation of ‘our knowledge of the system.’” John G. Cramer, “Interpreting Quantum Mechanics,” *Science Letters*, 221.4605 (July 1983), 6.

⁶³ Nick Herbert similarly notes the uncertainties in interpreting quantum equations. “What does the wave function really mean?” Nick Herbert, *Quantum Reality* (New York: Anchor Books, 1985), 128.

⁶⁴ G. C. Ghirardi, A. Rimini, and T. Weber, “Unified dynamics for microscopic and macroscopic systems,” *Physical Review D* 34 (1986), <http://www.qpt.org.uk/index3.php?id=5&id2=17> (accessed April 13, 2008)

Relativity (SR).

In 1997, Anton Zeilinger and collaborators at the University of Innsbruck in Austria conducted a “quantum teleportation.” The essential information contained within one of two entangled photons was transmitted instantaneously over a distance, materializing in the form of a third photon identical to the first. At the same instant, the first photon disappeared. Again, the influence causing the nonlocal change occurred at a superluminal speed. The result of this Star Trek “beaming” was published in *Nature* magazine in 1997.⁶⁵ This last test could not be as easily explained away as Aspect’s work. Quantum nonlocality is now empirically verified.

Quantum Nonlocality, Property Theory, and Holism

Some theoreticians argue that property theory has a role in interpreting quantum phenomena. Others suggest that quantum nonlocality may be interpreted as a holistic, nonseparable relational issue.

A property theory perspective does not necessarily detract from our Platonic information thesis. A relational intrinsic property can be attributed to Platonic entities. From this perspective, we could argue that a Platonic form’s intrinsic property (e.g., circle shape) is extrinsically expressed in a spacetime instantiation. Similarly, an

⁶⁵Anton Zeilinger, “Experimental Quantum Teleportation,” *Nature* 390 (December 1997), http://books.google.com/books?id=_JnrtbEGDNAC&pg=RA1-PA40&lpg=RA1-PA40&dq=%22Anton+Zeilinger,+%E2%80%9CExperimental+Quantum+Teleportation,%E2%80%9D+%22&source=bl&ots=kLp2b7Rsnt&sig=nBsmczwoUzI82uPkmOZ2Isz-RvI&hl=en&ei=jp7PSZbcF-nlnQeLi6njCQ&sa=X&oi=book_result&resnum=2&ct=result#PRA1-PA40,M1 (accessed February 16, 2008)

interpretation of nonlocality as a nonseparable, relational condition can be re-expressed as the influence of non-spacetime Platonic forms.

Quantum nonlocality and property theory. Recently, Brian Weatherson (Philosophy Department, Cornell University) examined contemporary uses of property theory and found that the definitions elaborated by David Lewis are still relevant. “The intrinsic properties of something depend only on that thing [itself], whereas the extrinsic properties of something may depend, wholly or partly, on something else.”⁶⁶

Summarizing Einstein’s famous objection to entanglement, in the EPR paper, Richard Healey (Philosophy Department, University of Arizona) reminds us that he assumed a classical physics understanding of the state of a whole system as combining individual component states, not adding something.⁶⁷ Fifty years after EPR, Howard equivalently restates the EPR principle as “The real state of the pair AB consists precisely of the real state of A and the real state of B, *which states have nothing in to do with one*

⁶⁶ Brian Weatherson quoting David Lewis, “A sentence or statement or proposition that ascribes intrinsic properties to something is entirely about that thing; whereas an ascription of extrinsic properties to something is not entirely about that thing, though it may well be about some larger whole which includes that thing as part. A thing has its intrinsic properties in virtue of the way that thing itself, and nothing else, is. Not so for extrinsic properties, though a thing may well have these in virtue of the way some larger whole is. The intrinsic properties of something depend only on that thing; whereas the extrinsic properties of something may depend, wholly or partly, on something else.” Brian Weatherson, “Intrinsic vs. Extrinsic Properties,” *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, (Stanford: Metaphysics Research Lab, 2008), <http://Plato.stanford.edu/entries/intrinsic-extrinsic/> (accessed February 16, 2008)

⁶⁷ “In classical physics ... if a physical system is composed of physical subsystems, then both the composite system and its subsystems will be assigned states... [and] the state of the whole will not be independent of those of its parts.... If a system is composed of two subsystems, A and B, then it will satisfy a principle [first] formulated by Einstein [in the 1935 EPR paper].” Richard Healey, “Holism and Nonseparability in Physics,” *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, (Stanford: Metaphysics Research Lab, 2009), <http://Plato.stanford.edu/entries/physics-holism/> (accessed July 20, 2008)

another” [my italics].⁶⁸ In this EPR-like perspective, there is no supervenience⁶⁹ of the whole system upon its components. Because the EPR deduction of nonlocal entanglement implies supervenience and contradicts separability, the paper argued that some unknowns (Bohm’s “hidden variables”) are missing in quantum mechanics. Healey finds convincing explanations of quantum nonlocality as either “metaphysical property holism”⁷⁰ or “spatiotemporal nonseparability.” The former implies that an entangled system is more than the sum of its parts.

Healey notes that, as EPR found, the quantum state of an entangled particles system does “not conform to these [separability] expectations.” In fact, a “system’s quantum state ... has a role in specifying some of its [own] categorical properties”⁷¹ Clearly, this has “metaphysical significance if a system’s quantum state plays a role in specifying its categorical properties.” As EPR stressed, the whole (quantum state) seems to determine values of some of its parts.⁷²

This threat to state separability was “one reason why Einstein denied that a

⁶⁸ Healey, *The Philosophy of Quantum Mechanics: An Interactive Interpretation*, 6.

⁶⁹ Supervenience is understood as “*A-properties supervene on B-properties if and only if a difference in A-properties requires a difference in B-properties* [my italics]—or, equivalently, if and only if exact similarity with respect to *B-properties guarantees* exact similarity with respect to *A-properties*.” Brian McLaughlin and Karen Bennett “Supervenience”, *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, (Stanford: Metaphysics Research Lab, 2008), <http://plato.stanford.edu/archives/fall2008/entries/supervenience/> (accessed July 20, 2008)

⁷⁰ “Physical Relational Holism: There are physical relations between some physical objects that do not supervene on their qualitative intrinsic physical properties.” Healey, *The Philosophy of Quantum Mechanics: An Interactive Interpretation*, 5.

⁷¹ Ibid, 7.

⁷² Ibid, 2.

quantum system's real state is given by its quantum state ... [Under the] rival Copenhagen interpretation, the quantum state gives a system's real dynamical state by specifying that it contains just those ... intrinsic quantum dynamical properties to which it assigns probability 1." This leads, according to Healey, to "physical property holism."⁷³ The composite determines the state of its components.

Healey points to the Bohmian Mechanics assumption of "hidden variables" as one way to get around separability.⁷⁴ Considering the Aharonov-Bohm Effect,⁷⁵ he argues that "there need be no action at a distance if the behavior of both the charged particles and electromagnetism are [considered to be] nonseparable processes."⁷⁶ In Healey's view, "nonseparability" can be interpreted as possibly varying magnetic field values extending "between" theoretically separated points in spacetime.⁷⁷ And, he notes that yet-to-be-proven string theory does not eliminate the quantum nonseparability problem.⁷⁸

⁷³ Here, "a pair of fundamental particles may have the intrinsic property of being spinless even though this is not determined by the intrinsic properties and relations of its component particles." Ibid, 10-11.

⁷⁴ "If one entertains a theory that supplements the quantum state by values of additional 'hidden' variables, then the quantum mechanical probabilities would be taken to arise from averaging over many distinct hidden states.... The best know example ... is the Bohm theory, where the 'hidden' properties are spatial positions and in each specific experimental context all probabilities are 0 or 1." Ibid, 11.

⁷⁵ The effect is a "quantum mechanical prediction that an interference pattern due to a beam of charged particles could be altered by the presence of a constant magnetic field in a [nonlocal] region from which the particles were excluded. The effect has since been experimentally demonstrated." Ibid, 14.

⁷⁶ Ibid, 14.

⁷⁷ Thus, "extensive holism or nonseparability" noted in quantum field theory can be explained as the result of "fundamental quantities in quantum field theory [which] are vacuum expectation values of products of field operators defined at various spacetime points. The field can be reconstructed out of all of these." Ibid, 14.

⁷⁸ Ibid, 17.

In another study, Michael Esfeld (Philosophy Department, University of Lausanne) develops a metaphysical interpretation of physical relations which significantly diminishes or eliminates a role for intrinsic properties in quantum mechanics. Although his conclusions differ from Platonic assumptions of this thesis, they contribute to it indirectly. For Esfeld, QM presents us with two alternatives: either physical phenomenon have unknown intrinsic properties or they are only relations. Quantum mechanics inclines us to the second view. “Quantum theory supports metaphysics of relations by speaking against intrinsic properties on which the relations ... supervene.”

Accordingly, Esfeld proposes a “metaphysics of relations [see the next section, below] that dismisses intrinsic properties of relata which are a supervenience basis for the relations.”⁷⁹ He points to John Wheeler’s “geometrodynamics” (1962) which described everything as configurations of the “four-dimensional continuum.”⁸⁰ Although, as Esfeld notes, Wheeler’s scheme was later rejected as incomplete, it does demonstrate that we can have a relational model of objects such as particles and quantum states “without intrinsic properties.”⁸¹

⁷⁹ “There are intrinsic properties but we cannot know them. [Or,] all there is to the physical things at the basic level is the relations in which they stand,” Michael Esfeld “Do Relations Require Underlying Intrinsic Properties? A Physical Argument for Metaphysics of Relations,” *International Journal for Ontology and Metaphysics*, 4 (2003), <http://www.unil.ch/webdav/site/philo/shared/DocsPerso/EsfeldMichael/2003/Metaphysica03.pdf> (accessed September 12, 2008)

⁸⁰ Wheeler proposed a “four-dimensional continuum ... [where] slow curvature describes a gravitational field ... geometry with a different curvature describes an electromagnetic field ... a knotted-up region of high curvature describes a concentration of charge and mass-energy that moves like a particle.” Ibid, 12.

⁸¹ Ibid, 12.

Nonlocality, Holism, and Relational Quantum Mechanics

A few theoreticians suggest that there is no space between apparently separated entangled particles. For example, Brian Greene (Physics Department, Columbia University) notes that “space cannot be thought of as ... intervening space.... [distance] does not ensure that two objects are separate ...[because of] entanglement.”⁸²

Vassilios Karakostas (Department of Philosophy and History of Science, University of Athens) interprets quantum nonlocality holistically. Although quantum level interaction produces entanglement, entanglement itself does not require interaction. Entanglement “does occur in the absence of any interactions ... entangled correlations among the states of various physical systems do not acquire the status of a causally dependent relation ... their delineation is rather determined by the entangled quantum state itself which refers directly to the whole system. [This is] a genuine quantum mechanical instance of holism: there exist properties of entangled quantum systems which ... characterize the whole system but are neither reducible to nor implied by or causally dependent on the local properties of its parts.”⁸³ The parts of an entangled system depend upon the whole rather than the reverse. Karakostas additionally argues

⁸² For example, Greene describes the revision that action-at-a-distance can have on our concepts of separating space, “Results from theoretical and experimental considerations ... support the conclusion that the universe admits interconnections that are not local ... *space cannot be thought of as ... intervening space*, regardless of how much there is, *does not ensure that two objects are separate, since quantum mechanics allows an entanglement* [my italics], a kind of connection, to exist between them.” Brian Greene, *The Fabric of the Cosmos* (New York: Vintage Books, 2005, 80.

⁸³ Vassilios Karakostas, “Forms of Quantum Nonseparability and Related Philosophical Consequences,” *Journal for General Philosophy of Science* 35 (2004), http://philsci-archive.pitt.edu/archive/00002152/01/V.E._KARAKOSTAS.doc (accessed September 13, 2008)

that physical systems are realized as context-dependent. Quantum entities are not “things-in-themselves.” Their wholeness is mind-independent and “veiled” from perception. “Any discussion concerning ... whole is necessarily ... ontological, metaphysical ... the only confirmatory element about it [is] the network of interrelations which connect its events.”⁸⁴

Richard Healey finds that nonlocal entangled systems can be interpreted holistically. “When one performs measurements of spin or polarization on certain separated quantum systems. The results ... exhibit patterns of statistical correlation that resist traditional causal explanation.”⁸⁵ These correlations suggest “spatiotemporal nonseparability.”⁸⁶ He suggests that quantum entanglement⁸⁷ may not be truly “nonlocal” because something (shared wave function, product of field operators, etc.) connects apparently spatially separated particles.

Joseph Berkovitz (Philosophy Department, University of Maryland) and Meir

⁸⁴ The “quantum objects can not be conceived of as ‘things-in-themselves’ ... Instead, they represent carriers of patterns or properties which arise in interaction with their experimental context/environment, or generally, with the rest of the world ... their existence depends on the context into which they are embedded and on the abstractions we are forced to make in any scientific discussion.... Although nonseparability ... clearly implies that wholeness is a fundamental aspect of the quantum world, nonetheless, neither theory nor experiment can disclose the exact fabric of this wholeness it can safely be asserted that reality thought of as a whole is not scientifically completely knowable or it is veiled ... it can neither be quantified nor computed or measured from the outside. Any discussion concerning the nature of this undissectable whole is necessarily of an ontological, metaphysical kind, the only confirmatory element about it being the network of interrelations which connect its events.” Ibid, 298–306.

⁸⁵ Richard Healey, “Holism and Nonseparability in Physics,” *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, (Stanford: Metaphysics Research Lab, 2008), <http://plato.stanford.edu/entries/physics-holism/> (accessed October 11, 2008)

⁸⁶ “Nonseparability: Some physical process occupying a region R of spacetime is not supervenient upon an assignment of qualitative intrinsic physical properties at spacetime points in R.” Ibid, 8.

⁸⁷ Schrodinger first named the predicted quantum nonlocality “entanglement” in 1935.

Hemmo (Philosophy Department, University of Haifa) argue that quantum phenomena can be interpreted from a “relational modal” perspective. They claim that this point of view enables them to “solve the measurement problem and ... reconcile[s] quantum mechanics with the special theory of relativity.” In the process, they reject local properties and argue that entities should be viewed in terms of relations. The assumption of a local property was basic to the EPR argument for QM incompleteness. Berkovitz and Hemmo “reject ... presuppositions ... that properties are ... local and always have definite joint probabilities ... [instead, they] argue that a violation of these assumptions [locality] could naturally be obtained in a relational modal interpretation which assigns only relational properties to systems.”⁸⁸

Michael Esfeld argues that quantum entanglement necessitates relational descriptions. The empirical verification of entanglement (for example, Aspect, 1982) means that there are no individual intrinsic properties of entangled particles, instead there are “only correlations between the conditional probability distributions of the state-dependent properties of the quantum systems.”⁸⁹ In addition, the relation of hidden

⁸⁸ Joseph Berkovitz and Meir Hemmo, “Modal interpretations of quantum mechanics and relativity: A reconsideration,” *Foundations of Physics* (March 2005), <http://philsci-archive.pitt.edu/archive/00001993/02/Berkovitz@Hemmo.FoundPhys.pdf> (accessed September 12, 2008)

⁸⁹ “If we take the quantum state description to tell us something about the properties of quantum systems, entanglement is to say that the quantum systems in question do not have state-dependent properties such as position, momentum or spin angular momentum in any direction each; state-dependent are all and only those properties of a physical system that can change during the existence of the system. Instead, there are only correlations between the conditional probability distributions of the state-dependent properties of the quantum systems in question. These probability distributions are completely determined only by the global state of the systems in question taken together. Quantum theory does not include any properties of each quantum system taken separately that are a supervenience basis for these correlated probability distributions. These correlations, and thus entanglement, are independent of spatio-temporal distance.” Esfeld, “Do Relations Require Underlying Intrinsic Properties? A Physical Argument for Metaphysics of

variables to the components of an entangled system “requires intrinsic properties on which these correlations supervene.”⁹⁰

Relational quantum mechanics (RQM) restates several basic QM principles. From an RQM perspective, a statement about a quantum event such as “A has a value x” must be rephrased as “A has the value x for B.” By itself, “A has a value x” is meaningless. All statements about a change to a system must specify the interaction involved in the change.⁹¹ A test apparatus detects the presence of an electron. That device should be included in a description of the measured state of the electron. Consistent with RQM, hidden variable interpretations seek to include otherwise missing interactions in explaining entanglement.

Discussing the impact of Bell’s Inequalities on a hidden variables interpretation, Esfeld finds that “Bell’s theorem does not rule out hidden variables that satisfy separability.... If [we postulate] hidden variables that establish a causal connection with any of these [explanations: superluminal, backwards causation, or a joint cause], then [these] hidden variables ... provide for intrinsic properties which are a supervenience

Relations,” 13.

⁹⁰ “If there are hidden variable, all the descriptions that ... physical theory can give of them may be relational...explaining the quantum correlations in terms of hidden variables...requires intrinsic properties on which these correlations supervene.” Ibid, 15.

⁹¹ “The apparent contradiction between the two statements that a variable has or hasn’t a value is resolved by indexing the statements with the different systems with which the system in question interacts.” Frederico Laudisa and Carlo Rovelli, “Relational Quantum Mechanics,” *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, (Stanford: Metaphysics Research Lab, 2008), <http://plato.stanford.edu/archives/fall2008/entries/qm-relational/> (accessed July 26, 2008)

basis for the correlations.”⁹²

As he notes, a “hidden variables” theory (as well as any other plausible physical explanation of quantum entanglement) would satisfy Quine’s requirement in “Two Dogmas of Empiricism” that “any statement can be held true come what may, if we make drastic enough adjustments elsewhere in the system.”⁹³

Esfeld finds that David Mermin’s interpretation of quantum mechanics which presents a “world of correlations without describing intrinsic properties of the correlate” is reasonable but unempirical.⁹⁴ Instead, Esfeld finally argues that we must accept the empirically given evidence of quantum mechanics and not expect additional factors.⁹⁵ Esfeld’s approach would exclude abstract mathematical objects and Platonic entities. However, like Platonism, his RQM perspective emphasizes an outside spacetime connectivity.

⁹² There is “a high metaphysical price [to pay for hidden variables]. One can try a causal explanation of the correlations in question as an alternative to admitting quantum entanglement. One has to claim that (a) correlated quantum systems are directly connected by superluminal interaction, or that (b) there is backwards causation, or that (c) there is a common cause somewhere in the intersection of the past lightcones that coordinates the behavior of the quantum systems with parameters that will be measured on them. If [we postulate] hidden variables that establish a causal connection with any of these types, then there are hidden variables that provide for intrinsic properties which are a supervenience basis for the correlations.” Esfeld, “Do Relations Require Underlying Intrinsic Properties? A Physical Argument for Metaphysics of Relations,” 17.

⁹³ Ibid.

⁹⁴ Mermin argues that “the correlate that underlie those correlations lie beyond the descriptive powers of physical science...*in our description of nature the purpose is not to disclose the real essence of the phenomena.* [my italics].Ibid, 19.

⁹⁵ “There is no need for the correlated quantum systems [as in entanglement] to have intrinsic properties over and above the correlations in which they stand.... There is no gap between epistemology and metaphysics: we can in principle know all there is, because we have no reason to believe that there is more to the things at the basic level of the world than the relations in which they stand.” Ibid, 23.

Thomas Filk (Institute for Theoretical Physics, Freiburg) tries to avoid the nonlocal implications of Bell's Inequalities and finds "hidden variable" explanations feasible. Arguing that QM entanglement may be interpreted as local, he points out that "the wave function itself is interpreted as encoding the 'nearest neighbor' [local] relations between a quantum system and spatial points." This means that spatial position is "a purely relational concept ... a new perspective onto quantum mechanical formalism where many weird aspects, like particle-wave duality, nonlocality of entanglement, and the 'mystery' of the double-slit experiment, disappear. This perspective circumvents the restrictions set by Bell's inequalities ... *a possible (realistic) hidden variable theory based on these concepts can be local and at the same time reproduce the results of quantum mechanics* [my italics]." ⁹⁶ Similarly, we could say that accurate probabilistic predictions of measurement results for an entangled pair can be made without specifying the separating distance between the members of the pair. Focusing on the relations between the members of the pair, enables us to more acceptably express a hidden variable explanation for the now-local entanglement phenomena.

This non-spatial or aspatial perspective can be seen in another relational approach to quantum theory explained by Carlo Rovelli and Federico Laudisa and as one that "discards the notions of absolute state of a system, absolute value of its physical quantities, or absolute event[s] ... [and] describes ... the way systems affect each

⁹⁶ Thomas Filk, "Relational Interpretation of the Wave Function and a Possible Way Around Bell's Theorem," *International Journal of Theoretical Physics*, 45.6 (2006), <http://arxiv.org/abs/quant-ph/0602060> (accessed August 6, 2008)

other ... in physical interactions. The physical content of quantum theory is ... the net of relations connecting all different physical systems.”⁹⁷

In another approach to RQM, Michel Bitbol ⁹⁸ suggests that these theories could be more naturalistic if they focus on relations as the collective “probabilistic prediction [by possibly] several physical observers.” However, these relational QM views are held by a minority. Most theoreticians accept nonlocality and Bell’s conclusions.

In summary, several contemporary philosophers argue that quantum mechanical phenomenon may be reinterpreted in terms of property theory and/or from a relational perspective. Explanatory questions about the supervenience of quantum systems upon their components such as entanglement and the nonlocal or local understanding of indirect influences such as the Aharonov-Bohm Effect remain unanswered. However, we can posit an intrinsic relational attribute for the Platonic information that influences the measurement results of quantum phenomena.

⁹⁷ “Relational quantum mechanics is an interpretation of quantum theory which discards the notions of absolute state of a system, absolute value of its physical quantities, or absolute event. The theory describes only the way systems affect each other in the course of physical interactions. State and physical quantities refer always to the interaction, or the relation, between *two* systems. Nevertheless, the theory is assumed to be complete. The physical content of quantum theory is understood as expressing the net of relations connecting all different physical systems.” Frederico Laudisa and Carlo Rovelli, “Relational Quantum Mechanics”, *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, (Stanford: Metaphysics Research Lab, 2008), <http://plato.stanford.edu/archives/fall2008/entries/qm-relational/> (accessed August 6, 2008)

⁹⁸ The problem “of formulating RQM ... naturalistic[ally]... [depends upon the existence of a] super-observer which does not partake of the naturalized status of ordinary observers ... [this problematic view] is solved by substituting functional reference frames for physical observers.... Instead of being relative to physical observers, statements about the state vector of physical systems arerelative to well-defined projects of probabilistic prediction which may be embodied by several physical observers.” Michel Bitbol, “Physical Relations or Functional Relations? A non-metaphysical construal of Rovelli’s Relational Quantum Mechanics,” *Philosophy of Science Archives* (Sept. 11, 2007), <http://philsci-archive.pitt.edu/archive/00003506/01/RelationsRovelli.pdf> (accessed August 7, 2008)

Non-Hidden Variable Explanations of Quantum Nonlocality

Conventional interpretations (e.g., Copenhagen) of quantum theory accepted the predictions of EPR and welcomed the probabilistic verification of nonlocality in Bell's theorem. However, their explanations for QM nonlocality vary:

- Nonlocality is an integral feature of QM.
- Nonlocality indicates geometric relational acausality
- Nonlocal effects are atemporal.
- Apparently nonlocal events are actually local.
- There are superluminal causal links.
- Nonlocal quantum events are relations between causal processes.

Each approach attempts to resolve philosophic questions raised by QM nonlocality. These views are summarized below. This thesis proposes a new information-theoretic explanation for quantum nonlocality, Platonic interpretations.

Nonlocality is Integral to Quantum Reality

Many theoreticians assume that entanglement involves no “hidden variables” and there are no undetected connections (e.g., no Bohmian “pilot wave”) between distantly entangled particles.⁹⁹ Bohr, Heisenberg, and many others accepted the predictions of EPR as consistent with QM.

In the *Trouble with Physics*, Lee Smolin (Perimeter Institute for Theoretical

⁹⁹ Bohr, Heisenberg, and many others accepted the predictions of EPR as consistent with QM.

Physics, University of Waterloo) interprets space as discrete instead of continuous. In his model, the unit or smallest volume of space is 10^{-99} cm^3 , the cube of the Planck length (10^{-33} cm). “Links” join the nodes of a “spin network” in Loop Quantum Gravity or “LQG.” Here, link spins are the quantum numbers that characterize an area of space. Smolin and others working on LMQ, propose three or more spatial dimensions and one time dimension. A particle is defined by spin network states.¹⁰⁰

In the work, Smolin argues that nonlocal causality is basic to quantum gravity. He refers to the “causal dynamical triangulations” model of Loll and Ambjorn which produces “classical spacetime with three dimensions of space [from a] quantum world based only on discreteness and causality.” In the future, Smolin predicts, “[theories will describe] the quantum universe in terms of discrete events and their causal relations ... causality will survive at a level in which space will no longer be a meaningful concept ... [in a new] relational quantum theory ... [that is] nonlocal, or ... extra-local ... space ... will ... be seen only as [a] description for certain kinds of universe, in the same way that thermodynamic quantities such as heat and temperature are meaningful only as averaged descriptions of systems containing many atoms. The idea of [quantum] ‘states’ will have no place in *the final theory, which will be framed around the idea of processes and the information conveyed between them and modified within them* [my italics].”¹⁰¹

Fergus Ray-Murray (PhD Candidate, Physics Department, Bristol University) notes, “quantum systems show correlations over such distances that it is very difficult to

¹⁰⁰ Smolin, *Three Roads to Quantum Gravity*, 249-254.

¹⁰¹ Ibid.

reconcile them with the picture of time painted by relativity and the picture of cause and effect with which we are all familiar.”¹⁰² He argues that nonlocal “entanglement seems to be necessary to explain the results of the ... two slit experiment, which have ... erroneously... been explained in terms of Heisenberg Uncertainty.”¹⁰³ And, John Barrow (Mathematics Department, Cambridge University) finds nonlocality characteristic of the quantum world. Unlike the local “non-quantum world [where] fundamental forces of Nature, like gravity, [that] diminish in strength with increasing distance ... from their source ... when we look at the quantum world of elementary particles, we discover that the world is nonlocal. This is the import of Bell’s theorem.”¹⁰⁴ As Barrow indicates, in the macroscopic (approximately Newtonian) world, locality is expressed as an indirect relationship between the strength of many forces (e.g., gravity) and the distance from their source. Differently, nonlocal quantum entanglement effects are unaffected by separating distance between the entangled pair (particles, systems, etc.).

Nonlocality Interpreted as Geometric Relational Acausality

Michael Silberstein (Philosophy Department, Elizabethtown College), W.M. Stuckey (Physics Department, Elizabethtown College), and Michael Cifone (Philosophy Department, University of Maryland) jointly propose a geometric, *non-Bohmian hidden variable account* of QM. Their “block world (BW) ... [including] an acausal and non-

¹⁰²Fergus Ray-Murray, “Quantum Entanglement and Causality,” <http://fergusmurray.members.beeb.net/Causality.html> (accessed March 12, 2008)

¹⁰³ Ibid.

¹⁰⁴ John D. Barrow. *New Theories of Everything* (Oxford: Oxford University Press, 2007), 226–227.

dynamical characterization and explanation of entanglement ... [whose] *EPR correlations are determined by the spacetime relations instantiated by the experiment* [my italics] understood as a spatiotemporal whole ... [in their model] there are no faster than light ‘influences’ or ‘productive’ causes between space-like separated events...these relations collapse the matter-geometry dualism.”¹⁰⁵ An interaction with a system immediately creates a set of purely geometric relations among things in a spacetime frame (points, particles, etc.) that can be detected as EPR correlations. Although this thesis is not at all like that of Silberstein, it too incorporates the idea of interaction-as-an-instantiator but in a different, Platonic sense.

Nonlocal Events are Atemporal

In a contribution to a 70th birthday volume (1949) for Albert Einstein, mathematician Kurt Gödel, famous for his Incompleteness Theorems and a close friend of Albert Einstein at Princeton, determined that a valid reformulation of relativity equations (in a “rotational universe”) allow time travel into the past and preclude absolute

¹⁰⁵ “[We propose] “a hidden-variables statistical interpretation of a sort ... but ...we are not primarily motivated by saving locality. we explain entanglement as a feature of the spacetime geometry ... However our view is nonlocal [because] it violates the locality principle ... [that] the result of a measurement is probabilistically independent of actions performed at space-like separation from the measurement.... EPR correlations are determined *by* the spacetime relations instantiated by the experiment, understood as a spatiotemporal whole ... our geometrical quantum mechanics provides for an *acausal*, *global* and *nondynamical* understanding of quantum phenomena.... Since our view respects the causal structure of Minkowski spacetime in the sense that there are no faster than light “influences” or “productive” causes between space-like separated events as there are in Bohm ... each family of trajectories characterizes the distribution of spacetime *relations*, we take those relations to be a timeless ‘block,’ these relations collapse the matter-geometry dualism, therefore, our geometrical quantum mechanics provides for an *acausal*, *global* and *nondynamical* understanding of quantum phenomena.” Michael Silberstein, W.M. Stuckey and Michael Cifone, “An Argument for 4D Blockworld from a Geometric Interpretation of Nonrelativistic Quantum Mechanics” *PhilSci Archives* (2007), http://philsci-archive.pitt.edu/archive/00003214/01/BW_from_NRQM.pdf (accessed March 12, 2008)

or intuitive time.¹⁰⁶ If we accept Gödel's argument,¹⁰⁷ quantum phenomena including nonlocality are atemporal.

Recent articles by Antoine Suarez and others at the Center for Quantum Philosophy in Zurich (published in the *Physical Letters*) suggest that nonlocality necessitates timelessness. "Experiments with moving beam-splitters demonstrate that there is no real time ordering behind the nonlocal correlations. In Bell's world there is no 'before' or 'after.'"¹⁰⁸

In the *Road to Reality*, Roger Penrose (Mathematical Institute, Oxford University) contends that contemporary physics postulates that timeless, limitless, active-everywhere

¹⁰⁶ Palle Yourgrau, *A World Without Time* (Cambridge: Basic Books, 2005), 128–135. Yourgrau also notes that Gödel's position is logically similar to ontological arguments for the existence of God. Brian Green, *Fabric of the Cosmos* (New York: Vintage Books, 2005), points out that Gödel was the first of several thinkers who concluded that Relativity theory permitted time travel. 460. Also, see Feferman, et al, *Kurt Gödel: Collected Works*, Vol. III, "Lecture on Rotating Universes" (New York: Oxford University Press, 1995), 267 - 287.

¹⁰⁷ Gödel argued that under Special Relativity (SR), spacetime (st) excludes an objective "now" (no reference frames are preferred). But, McTaggart's "A" series of past-present-future relationships requires a "now." If SR is valid, there is no "intuitive time." Under General Relativity (GR), reference frames that include matter are preferred because gravity is st curvature. If we coordinate these reference frames, an objective "cosmic time" exists. Some solutions of GR equations allow a universe in which all matter is rotating relative to a "free" gyroscopic-like inertial field. In these "rotating universes ... compass of inertia ... rotates in the same direction relative to matter." Here, no absolute cosmic time can exist. He also considered "rotating universes which [are] ... static and spatially homogeneous [with a] cosmological constant < 0 ." Gödel showed that in one possible "Gödel universe" the geometric st distortion is large enough to close st paths. If an object travels quickly enough ($1/\sqrt{2} \times c$) along a closed st path, it would arrive back at its own space in the past. In this universe, events always exist; they are never truly 'past.' Therefore, the possibility of time travel makes intuitive time (with A series relationships) impossible. Finally, Gödel argues (similarly to his Incompleteness proof) that the absence of time in one universe necessitates the absence of time in all possible universes. See Kurt Gödel, "A Remark about the Relationship Between Relativity Theory and Idealistic Philosophy" in *Albert Einstein, Philosopher-Scientist*, ed. P. A. Schilpp (La Salle: Open Court, 1949), 204- 287.

¹⁰⁸ Antoine Suarez, A. Stefanov, H. Zbinden, and N. Gisin, "Is There a Time Ordering Behind Nonlocal Correlations?" in *Quantum Philosophy Theories* (2007), http://www.bioprodownloads.com/pdf/ResearchStudy_Oct20-01_RealTimeOrdering.pdf (accessed August 2, 2008)

conditions (including nonlocal) and substances (wave functions, entangled systems, Higgs field, mbranes, etc.) underlie existence.¹⁰⁹ He finds that “causality violations in which ‘closed timeline curves can occur, and it becomes possible for a signal to be sent from some event into the past of that same event.’”¹¹⁰ For a summary of his own Platonism, see “Roger Penrose,” under “Physical Platonism” below.

Nonlocal Events are Superluminal Messages

A few suggest that measurement notifications travel instantly across distances separating entangled particles. Entangled particles can be subject to a superluminal causal link. According to Ray-Murray, “It may be possible to avoid the [EPR] paradoxes ... while accepting the existence of superluminal causal links ... because we have no real control over the links. We cannot, for instance, use them to send superluminal signals of any kind.”¹¹¹ Tim Mauldin (Philosophy Department, Rutgers University) also finds that “Superluminal signals must ... propagate into the past: the signal is received before it is sent. The conditions required for the possibility of such paradoxes are more complex than merely the existence of superluminal signals. Accordingly, violations of Bell’s inequality predicted by quantum mechanics do not allow superluminal signals. [However] even though nature may not allow superluminal signally, it does employ, according to Bell, superluminal causation ... [this] will pressure

¹⁰⁹ Penrose, *The Road to Reality, A Complete Guide to the Laws of the Universe*, 508, 591, 887.

¹¹⁰ Ibid, 409.

¹¹¹ Ray-Murray, “Quantum Entanglement and Causality,” *ibid*.

us to add more structure to space-time than Relativity says there is.”¹¹²

Here, relativity theory is not challenged because no signal passes between the separated, entangled particles. However, Julian Barbour interprets Alain Aspect’s experimental results as evidence of superluminal, causal contact. But a deeply troubled John Bell wrote the verified superluminal causal effect of nonlocal entanglement was “for me...the real problem of quantum theory.”¹¹³

Nonlocal Events are Relations Among Causal Processes. Attempting to unify general relativity (GR) and QM, Roger Penrose redefines quantum causality. Instead of real events connected by causal relations, he reverses the roles. Causal processes are real and the events, such as entanglement results, are only relations between the processes. In his model, space can be imagined as composed solely of light rays with space and time as relations between them. His “twister” theory produces spacetime from something other than ordinary space and time. Penrose defines twistors as “complex objects, like wave functions in quantum mechanics ... endowed with holomorphic and algebraic structure sufficient to encode space-time points.” According to Penrose, the theory “provides a background against which space-time could be meaningfully quantized” and reconciled

¹¹² Tim Maudlin, *Quantum Nonlocality and Relativity* (Oxford: Blackwell Publishers, 2002), 112–116.

¹¹³ ““But another problem is brought into focus ... any sharp formulation of quantum mechanics has a very surprising feature: the consequences of events at one place propagate to other places faster than light. This happens in a way that we cannot use for signaling. Nevertheless it is a gross violation of relativistic causality... the specific quantum phenomena that require such superluminal explanation have been largely realized in the laboratory ... especially by Aspect, Dalibard, and Roger, in Paris in 1982.... This is the real problem with quantum theory: the apparently essential conflict between any sharp formulation and fundamental relativity ... it may be that a real synthesis of quantum and relativity theories requires not just technical developments but radical conceptual renewal.” John Bell, *Speakable and Unsayable in Quantum Mechanics* (Cambridge: Cambridge University Press, 1987), 171-172.

with QM.¹¹⁴

Interpreting Quantum Hidden Variables as Something Else

A proposal to replace Bohm-deBroglie hidden variables-guiding equation with something else (i.e., Platonic entities) must provide or perform at least the same functions as existing guiding equation/hidden variable theories. Like the Bohmian and other hidden variable theories, a replacement must contribute to changing quantum mechanics from a statistical to a deterministic field. Several non-Bohmian hidden variable theories have been promoted. Some, including Bohm's, are nonlocal.¹¹⁵ All attempt to "[to obtain] quantum probabilities and correlations ... as averages over variables at some deeper level than those specifying the quantum state of a system."¹¹⁶

Thus, the replacement hidden variables must

- Operate nonlocally
- Provide superluminal causation (a Bell requirement for quantum mechanics)
- Provide the value of a particular quantum state for one particle when the corresponding value of the other one is measured.

These requirements are met by the Platonic model proposed in "Part 4

¹¹⁴ Penrose, *The Road to Reality, A Complete Guide to the Laws of the Universe*, 1003.

¹¹⁵ The existence of local hidden variables would counter Bell's theorem. "A number of proofs exist to the effect that positing certain types of hidden variables [local] would force probabilistic results at the quantum level that contradict the predictions of quantum theory." *The Cambridge Dictionary of Philosophy*, Second Edition, ed. Robert Audi (Cambridge: Cambridge University Press, 1999), 703.

¹¹⁶ Ibid.

Information Platonism” in this thesis.

Finding Platonism Among Interpretations of Quantum Nonlocality

As the section indicates, nonlocality is a generally recognized corollary of quantum theory and phenomena. Various views of nonlocality have been advanced as integral to QM mathematics, indicative of geometric relational acausality, evidence of quantum level atemporality, actually “local” events, superluminal causal links, and evidence that quantum events are relations between causal processes rather than objects. Only one of the views surveyed represents Platonism: Roger Penrose. For more about his unique version of Platonism, see “Roger Penrose” under “Physical Platonism” below.

Part Two: Modern Mathematical Realism and Platonism

Overview

Philosophers and mathematicians discuss “realism” and its often-equivalent, contemporary Platonism, in terms of mind-independent, external to space-time, abstract objects that continue to exist if the universe ceases to be.¹¹⁷ Many argue that “real” objects cannot be involved in causal relationships with physical objects. However, in their early classic Greek guise, Platonic “forms” were associated with phenomenal objects. Forms expressed the ideal characteristics (shape, extension, number, set-of-all-sets, etc.) that phenomenal objects partially instantiated. No object expressed all the characteristics of the form. In both the earlier and modern theories, forms are uncreated and only discovered or perceived incompletely by minds.

Many theorists have rejected any form of Platonism because of the connectivity problem. How can an external Platonic form (often referred to as a “universal”) be connected to or associated with a material object (also known as “physical particular”), or how can it cause or be involved in an instantiation in the physical world? Many have understandably concluded that the connectivity problem is unsolvable. Thus, Jeffrey Grupp¹¹⁸ argues that most Platonists contend that “universals” are connected to “particular objects” by an obscure “exemplification tie.” He finds that their assumption of “exemplification” does not solve the connectivity problem. Instead, they often assert that the connection is “primitive” without explaining how an unlocated universal form

¹¹⁷ Richard Tieszen, “Realism and Reason After Gödel,” unpublished work in-progress, 6-7.

¹¹⁸ Jeffrey Grupp, “The Impossibility of an Exemplification Tie Between Particulars and Universals,” 29.

(outside spacetime) can contact or be contacted by a located (within spacetime) particular object. Grupp “see[s] no solution” to the problem.¹¹⁹ Recognizing this difficulty, others have argued that the connectivity problem consigns Platonism to a sideline role unworthy of contemporary philosophical consideration. Addressing a single philosophical quantum problem from a Platonic perspective, this thesis proposes a way around the problem.

This section of the thesis introduces 20th and 21st century Platonism represented by several contributors, briefly highlighting its philosophical, mathematical and physical expressions.

Mathematical Realism

Mathematical realism has significantly influenced the foundations and philosophy of mathematics in the past century. This section introduces the field through a brief review of several contemporary examples.

James Robert Brown

James Robert Brown (Philosophy Department, University of Toronto) affirms the existence of Platonic entities, including organizing principles of the universe. He finds that “laws of nature are relations among universals ... among abstract entities which exist independently of physical objects, independently of us and outside of space and time. Laws on the Platonic view are not parasitic on existing objects and events. They have

¹¹⁹ Jeffrey Grupp, “The Impossibility of an Exemplification Tie Between Particulars and Universals,” *Metaphysica: The International Journal for Ontology and Metaphysics* 4.1 (2003), 27-38.

life ... of their own.”¹²⁰

Benjamin Callard

Benjamin Callard (Philosophy Department, Lehman College) points out that the most common objection to Platonism is empirical, that a “causal knowledge of these [mathematical] objects seems unintelligible.” How can we know about non-spatiotemporal mathematical objects? Rejecting Benacerraf’s unrealizable empirical criteria for a solution of this “problem of access” and Jerry Katz’s indication that it would be “senseless [to attempt] acquaint[ance] with atemporal abstract objects,” Callard argues that we should distinguish two ways to interact with the atemporal at instantiation: we change it or it changes us. Our minds operate in spacetime.

Callard finds that the “challenge is grounded in a principle inherited directly from philosophers like Descartes, Spinoza, and Leibniz ... that entities of radically diverse types [cannot] really cause changes to happen in one another.” Callard rejects this inherited understanding, arguing that there is “no problem with the idea of something being affected by an entity radically dissimilar from it. There is no conceptual difficulty with the idea that they impart energy to our brains, and that they do this ‘at a distance’ ... without contiguity relations.”

As Plato indicated, a mental recognition of Beauty or a mathematical object occurs in time. Platonic objects remain unchanging and non-spatiotemporal, but they are experienced in spacetime. In this mind-centered sense, Callard holds that Platonic

¹²⁰James Robert Brown, *Smoke and Mirrors: How Science Reflects Reality* (New York: Routledge, 1994),

causality reflected in the ability to have a mental image of the atemporal is reasonable.

He disagrees with Hale, finding that a connection is not impossible between the abstract Platonic realm and the physical.¹²¹

This argument will be mentioned later, in an explanation for the quantum expression of Platonic information. In this argument, Callard's role of the mind's perception is restated as the measurement/observation of a quantum state.

Michael Tooley

In *Causation: A Realist Approach* Michael Tooley (Philosophy Department, University of Colorado) argues for a Platonic interpretation of causality. His "Factual Platonism" assumes that universal, unobservable causes exist for observable events. He sees causation as "real" as the "theoretical entities" of physics such as electrons.

96-97.

¹²¹ "I argue that the idea of causal relations with fully Platonist objects is unproblematic.... Benacerraf [asks] how could abstract objects cause anything to happen or obtain in the material world? The Platonist's proposal is that we grasp or perceive the number five, and thereby come to know that it is prime, but though *in grasping it we are changed, we do not cause it to change* [my italics].... [In] Plato's theory of the Forms... something happens to the Form of Beauty [when] it is instantiated.... Platonists can admit that abstract objects are temporal ... They can still be necessary, permanent and unchanging, and this is the sense of 'atemporal' operative in classical Platonism... Many Platonists have ... reject[ed] the idea that the objects of mathematics need to influence our brains causally in order to produce knowledge. Others have granted that mathematical objects...to be known need to operate causally on our brains...and ... offered a 'new' ... abstract object ... All agree with Bob Hale...that 'the claim that we can and do literally perceive sets ... is [preposterous], if sets are conceived, as they usually are, to be abstract objects, outside of time and space.' [Differently] I argue that this claim is inherited from Descartes, Spinoza, and Leibniz... that 'entities of ... radically diverse types [cannot] really cause changes to happen in one another.' [T]here *is no problem with the idea of something being affected by an entity radically dissimilar from it* [my italics].... there is no problem with the idea of abstract objects effecting changes in us; *there is no conceptual difficulty with the idea that they impart energy to our brains, and that they do this 'at a distance', i.e., without the benefit of contiguity relations.*" Benjamin Callard, "The Conceivability of Platonism," *Philosophia Mathematica* 15. no.3,

[http://philmat.oxfordjournals.org.libaccess.sjlibrary.org/cgi/content/full/15/3/347?maxtoshow=&HITS=10&hits=10&RESULTFORMAT=&fulltext=Plato&searchid=1&FIRSTINDEX=0&volume=15&issue=3&re](http://philmat.oxfordjournals.org.libaccess.sjlibrary.org/cgi/content/full/15/3/347?maxtoshow=&HITS=10&hits=10&RESULTFORMAT=&fulltext=Plato&searchid=1&FIRSTINDEX=0&volume=15&issue=3&re sourcetype=HWCIT)
sourcetype=HWCIT (accessed August 5, 2008)

“Causation is that theoretical relation that determines the direction of the logical transmission of probabilities ... [it is the] bringing into existence of one event by another.” Viewing causality through a Platonic lens, he finds that “intuitively, one ... wants to speak of causal relations in such a simple universe [containing no change or motion].”¹²²

Susan Hale

Reviewing a Michael Resnick article on the nominalist-Platonist debate, philosopher Susan Hale (Philosophy Department, University of North Carolina) rejects the nominalist criticism of Platonism because “the conceptual presupposition of the distinction between mathematical and physical objects is endangered.” Instead, she points to an ontological overlap of mathematical and physical structures predicted by Heisenberg. Following on his suggestion, Hale argues that particles of “matter” are actually “ontologically derivative... [for particles] the relations of *divide* and *consist of* lost all literal meaning ... undermining the particle concept is undermining the concept of matter. Fundamental symmetry groups provide a natural choice of replacement concepts.” She notes, “we can conceive of these elementary, non-elementary particles as complicated states, perhaps as mathematically-described states of fields. The change Heisenberg proposes suggests that there is more continuity between the ontology of mathematics, the ontology of physics, and the ontology of objects of our everyday

¹²²Richard Smyth reviewing *Causation, a Realist Approach* by Michael Tooley in *Nous*, 27, no. 1. (March 1993), <http://links.jstor.org/sici?sici=0029-4624%28199303%2927%3A1%3C91%3ACARA%3E2.0.CO%3B2-0> (accessed August 5, 2008)

experience than many philosophers have believed there to be.”¹²³

Jerrold Katz

Jerry Katz (d. 2002, Linguistics Department, University of Arizona) affirms a model of mathematical realism in “What Mathematical Knowledge Could Be.” Finding many opponents of realism searching in the wrong place for counter arguments, Katz insists that we can “have mathematical and other formal knowledge when there is no possibility of making causal contact with the objects of such knowledge.” He hopes to “meet [the] epistemological challenge to realists and to give lie to ‘refutations’ of realism based on the fact that the aspatiality and atemporality of abstract objects puts them beyond our causal reach.”¹²⁴ Accepting the challenge raised by Benacerraf and others, Katz proposed a rationalist-realist dualism (of abstract and concrete objects) that views scientific knowledge as a priori. He distinguishes his form of dualism from that of mind and physicality. Rejecting the epistemological insistence upon causal connections, Katz argues that “in the case of realism, there is nothing corresponding to psycho-physical

¹²³ Susan C. Hale, “Elementarity and Anti-Matter in Contemporary Physics: Comments on Michael D. Resnik’s ‘Between Mathematics and Physics.’” in *PSA: Proceedings of the Biennial Meeting of the Philosophy of Science Association*, Symposia and Invited Papers (1990), <http://www.jstor.org.libaccess.sjlibrary.org/action/showArticle?doi=10.2307/193081&Search=yes&term=elementarity&term=%22between+mathematics+and+physics%22&term=d&term=physics&term=michael&term=contemporary&term=resnik%27s&term=anti-matter&term=comments&item=1&returnArticleService=showArticle&ttl=3&searchUri=%2Faction%2FdoBasicSearch%3FQuery%3DElementarity%2Band%2BAnti-Matter%2Bin%2BContemporary%2BPhysics%253A%2BComments%2Bon%2BMichael%2BD.%2BResnik%2527s%2B%2522Between%2BMathematics%2Band%2BPhysics%2522%26x%3D11%26y%3D13> (accessed June 7, 2008)

¹²⁴ Jerrold Katz, “What Mathematical Knowledge Could Be,” *Mind*, New Series, 104, no. 415, (Jul., 1995), <http://www.jstor.org/pss/2254639> (accessed June 7, 2008)

correlations and, hence, there is no pressure on realists corresponding to the pressure on Cartesians to explain or explain away the appearance of interaction between causally incommensurable objects.”¹²⁵

Katz accepts Benacerraf’s point that, as spacetime inhabitants, we cannot casually connect with abstract objects as we do with concrete objects. However, he notes that Benacerraf’s argument does not preclude knowing abstract objects in a different way than we know concrete objects, not by connecting with them but in some other way. Instead connecting by “senses,” Katz suggests that we connect to abstract mathematical objects (e.g., “number-theoretic facts”) in an “a priori” way.¹²⁶

Arguing that empirical criteria do not apply to our knowledge of abstract objects, Katz rejects Benacerraf’s claim that “the realist account of mathematical truth does not mesh with ‘our overall account of knowledge’ has no force against a realist account on which mathematical knowledge is purely a priori.”¹²⁷

Developing his position, Katz affirms that “the grounds for seeking an improved concept of mathematical knowledge may well be stronger than the grounds for seeking an improved concept of truth.”¹²⁸ He rejects Benacerraf’s “combinatorial” suggestion for a semantics that “treats the logical form of mathematical sentences and corresponding non-

¹²⁵ Ibid. 519-520.

¹²⁶ Ibid. 493.

¹²⁷ Ibid.

¹²⁸ Ibid. 494.

mathematical sentences in the same way.”¹²⁹

Finding nothing “in the natural world to which our knowledge can be causally connected” that corresponds to “numbers, propositions, and expressions (in the type sense),”¹³⁰ Katz appeals to the “light of reason” for mathematical knowledge.

But, Katz indicates, anti-realists including Gottlieb, Field, Chihara, and Dummett reject a rationalist epistemology because the approach (e.g., Gödel’s intuition) seems to them “like appealing to experiences vaguely described as ‘mystical.’”¹³¹ Katz understands this criticism because there is a mystery to knowing abstract objects. However, “a philosophical mystery is no grounds for crying ‘mysticism’”¹³² because our “cognitive faculties” are not limited to sensation. He notes that even Benacerraf recognized this when he remarked that “‘knowledge of general laws and theories, and through them, knowledge of the future and much of the past’” was inferentially based on observations of “medium sized objects.”

Katz recognizes that mathematical realism has “no plausible epistemology available to meet Benacerraf’s challenge.”¹³³ He proposes a solution. First, “like Benacerraf,” he “assumes that knowledge is true belief.” Next, Katz asserts that nothing in the “content of our mathematical belief can depend on contact with abstract

¹²⁹ Ibid.

¹³⁰ Ibid. 497-498.

¹³¹ Ibid. 499.

¹³² Ibid.

¹³³ Ibid. 500.

objects.”¹³⁴

Some version of “nativism” is needed but not Plato’s because his approach assumed the soul’s contact with abstract forms before life. Katz suggests that Chomsky’s model of innate language abilities is one model. A modification of the Chomskian approach would innately posit all the knowledge necessary for mathematical beliefs within the person. However, he does not completely endorse a Chomskian model.

Katz argues that mathematical propositions and the “facts which they are about” are abstract objects. Therefore, “mathematical truth is ... an abstract relation between abstract objects.”¹³⁵ As he had argued earlier for a way to “have knowledge of abstract objects,” Katz finds that “basing our knowledge of abstract objects on perceptual contact is misguided ... [because the] epistemological function of perceptual contact is to provide information about which possibilities are actualities.”¹³⁶ Differently, mathematical objects and relations “cannot differ from one world to another.” They are as they must be.¹³⁷

Richard Tieszen

Richard Tieszen (Philosophy Department, San Jose State University) provides a Platonic-like phenomenological view of the relations between abstract objects and

¹³⁴ Ibid.

¹³⁵ Ibid, 504.

¹³⁶ Ibid.

¹³⁷ Ibid.

material minds in “Consciousness of Abstract Objects.”¹³⁸ Reviewing Kurt Gödel’s and Roger Penrose’s insistence upon the necessary existence of abstract objects, Tieszen concurs with Gödel that the incompleteness theorems demonstrate the likely existence of abstract mathematical objects. But disagreeing with Penrose’s position, he rejects the notion that brain states can be “about” a body-external event or object.¹³⁹ Furthermore, he believes that trying to determine the material connection of the mind or brain with out-of-spacetime abstract objects may be futile.¹⁴⁰ Tieszen notes that many forms of “object-directed [thought] do not require that there be an object” and eventually concludes that “we can hold [to an abstract natural object for which] there is nothing ... that counts as evidence ... and continue ... to examine the matter of whether there could possibly be anything that could count as evidence.”¹⁴¹ He concludes that “the philosophy of mind [does] have a place for the consciousness of abstract objects.”¹⁴²

In his recent, “Mathematical Realism and Transcendental Phenomenal

¹³⁸ Richard Tieszen, “Consciousness of Abstract Objects,” in *Phenomenology and Philosophy of Mind*, ed. D.W. Smith and A. Thomasson (New York: Oxford University Press, 2005), 185 - 200.

¹³⁹ “I [am] using mind language [which is] very different from brain language. Brain states, viewed as purely physical phenomena, do not have aboutness. It is not part of the very nature ... of a particular neurochemical activity that it somehow refer outside of itself to some other thing ... describing ... neurochemical activity in the language of natural science we should not find that in addition to neurons and neurochemical interactions that there are ‘contents,’ noemata, meanings, and so on.” Tieszen, *ibid.*

¹⁴⁰ “We will not get very far with the question of the consciousness of abstract objects if from the onset we suppose that mind talk just is brain talk or even that the mind is in some crude way just the brain...how could a brain be in epistemic contact with an abstract object? If this is the question...we can probably close up the shop and go home now.” Tieszen, 186.

¹⁴¹ *Ibid.*, 198.

¹⁴² *Ibid.*, 199.

Idealism,”¹⁴³ Rick provides a modern post-Husserlian argument for the compatibility of mathematical realism and idealism: “constituted realism.” Viewing the divide from the perspective of 20th century developments in mathematics since Husserl, Rick sets out to “characterize some recent forms of mathematical realism, present some ... claims of transcendental phenomenological idealism ... and examine ... some of the issues about the compatibility of mathematical realism and transcendental phenomenological idealism.”¹⁴⁴

Starting his analysis, Rick defines mathematical realism and mathematical idealism. The former refers to “mind-independent abstract mathematical objects or truths.” These mathematical objects include “geometric objects, natural numbers, real numbers, complex or imaginary numbers, functions, groups, sets, or categories, and truths about these objects.” Although he does not specifically include “intentional objects” such as “meaning, propositions, ideas, concepts, or essences,” as many Platonists might, Rick does not exclude them from the possible realm of the mathematically real.¹⁴⁵ As he notes, “one can be a Platonist about extensional objects, intentional objects, or both,” sometimes “prioritize[ing] the relationship between the two ... that one ... is derivable from or dependent on the other.”¹⁴⁶ Oppositely, “standard” (non-phenomenological) mathematical idealism refers to the view that “mathematical objects

¹⁴³ Richard Tieszen, “Mathematical Realism and Transcendental Phenomenal Realism,” *Phenomenology and Mathematics* (forthcoming).

¹⁴⁴ Ibid., 1.

¹⁴⁵ Ibid., 3.

¹⁴⁶ Ibid., 4.

(which may be ‘abstract’ in some sense but not eternal or atemporal) are mind-dependent.”¹⁴⁷ For Rick, these two views are deeply incompatible.

Next, Rick explores the “mind-independence” implicit in “Mathematical Realism” in Husserl and post-Husserlian study. Generally, mathematical objects transcend minds. They are generally understood as existing independently of minds as immaterial, non-spatial, atemporal, and non-causal objects. As Rick notes, in the *Logical Investigations*, Husserl distinguishes “between real and ideal objects.” And, mentioning Husserl’s paper, “Universal objects and their self-constitution in universal intuitions,” Rick finds that Husserl “contrasts the kind of abstraction involved in setting into relief a non-independent moment of a sensible object with ‘ideational abstraction’ in which an ‘idea’ or ‘universal’, not a non-independent moment, is brought to consciousness.”¹⁴⁸

In at least one respect, Rick finds Husserl closer to Plato’s original understanding of the form than modern Platonists. Husserl differentiates “between the inexact and the exact, or the imperfect and the perfect ... [this] feature of Husserl’s distinction [has] a Platonic pedigree that is omitted from some modern versions of mathematical realism.” Unlike their instantiations in the observable world, Platonic forms were “exact and perfect.”¹⁴⁹

Rick finds that mathematical realists may “disagree about *which* mind-independent abstract or ideal mathematical objects exist.” Post-Husserlian developments

¹⁴⁷ Ibid.

¹⁴⁸ Ibid., 7.

¹⁴⁹ Ibid.

in modern set theory can amplify this disagreement because they force “philosophers to confront a ... new set of epistemological and ontological issues about mathematical realism.” They raise a new level of questions about “mind-independence.” For example “some of the existence axioms in Zermelo-Fraenkel set theory ... axioms of infinity, power set, and replacement ... show ... that very large transfinite sets exist ... not only ... denumerably infinite sets exist but also non-denumerably infinite sets ... then power sets of non-denumerably infinite sets, and so on ... transfinite sets transcend the possibility of being known on the basis of acquaintance with all of their members.” Therefore, “we should ask whether there are mind-independent abstract *infinite* objects. In particular, are there *actual, complete infinite sets*?” If the mind cannot “view” these transfinite sets, might they still exist? And, Rick notes that in addition to the “traditional worries about the axiom of choice ... with the replacement axiom we also have impredicative specification of sets.” Then, he asks should we therefore hold as part of our mathematical realism that impredicatively specified transfinite sets exist or not?”¹⁵⁰

If the Platonic realm extends beyond our human ability to instantiate a replica of the original form, can we still insist that such mathematical objects are “real”? Rick seems to suggest so. As he notes, “Gödel [was] prepared to be [a] realist[s] about full impredicative set theory with the axiom of choice ... [he] might be prepared to adopt a realism that goes beyond the existential commitments of a theory such as ZFC, arguing for ... new axioms to express more of what already exists in the universe of abstract,

¹⁵⁰ Ibid. 9-10.

mind-independent transfinite sets ... [he] suggests that the search for new axioms depends on sharpening or clarifying our intuition of the concepts concerning this existing realm of objects or truths.”¹⁵¹

Turning to “transcendental phenomenological idealism,” Rick finds ideal intentionality in Husserl’s philosophy, “Husserl says that the whole spatiotemporal world and each of its constituents is ... a merely intentional being. It is a being posited by consciousness in its experiences. *Each constituent of the world ... can be determined and intuited only as something identical through motivated multiplicities of appearances.... Beyond that it is nothing ... Consciousness constitutes the sense of objectivity ...* [T]his ... idealism it is not, Husserl says, a Berkeleyan subjective idealism. Rather, it is transcendental-phenomenological idealism. It recognizes that *not everything is constituted as a mental phenomenon* and it also recognizes the *role of the overlapping horizons of different egos in the constitution of a common, objective world*” [my italics].¹⁵²

According to Rick, for Husserl, the “objective world” is the consensus of conscious minds. Transcendental phenomenological idealism “*makes of objectivity a problem that is to be grasped from what is absolutely given.* It enjoins us to *investigate how consciousness constitutes the sense of objectivity.* We must now *engage in constitutional analysis ... for any kind of objectivity.*”¹⁵³ Again, the objective world is

¹⁵¹ Ibid. 10.

¹⁵² Ibid. 14–15.

¹⁵³ Ibid., 15–16.

determined by conscious effort. And, are the objects of mathematical realism, “ideal objects are also constituted as such by consciousness?”¹⁵⁴

At this point, we can ask, what exists that is not “constituted as a mental phenomenon?” And, do mathematically real objects exist outside conscious minds? Husserl may imply that they do not.

But Rick indicates “If what is experienced has the sense of being ‘ideal’, ‘non-mental’, ‘acausal’, ‘unchanging’, ‘non-spatial’, (possibly ‘partially given’) and ‘non-material’ then it must be experience itself that ... constitutes this sense. If mathematical objects are considered to be objects that existed before we became aware of them and that *would exist even if there were no human subjects then it must be the case that this sense of mathematical objects is constituted in a motivated and non-arbitrary manner ... we can now say that mathematical objects possess these features except that we must add the crucial qualification that they are constituted non-arbitrarily in this manner in the consciousness of the transcendental subject.*” And because mathematical objects may be experienced by minds, they not outside of time but instead are “omnitemporal.”¹⁵⁵ Here is a key point, “as transcendental phenomenological idealists we cannot speak about the existence of objects that are somehow outside of all possible appearance or outside of all possible consciousness, and hence outside of all possible time.” For Husserl, and perhaps Rick, mathematical objects depend upon their appearance in consciousness.

For Rick, this leads to “unique ... ‘Platonism’ about mathematics ... *constituted*

¹⁵⁴ Ibid., 17.

¹⁵⁵ Ibid., 18.

Platonism ... embedded within transcendental idealism ... [wherein] we look to the transcendental ego as the source (origin) of Platonism about logic and mathematics, where logic and mathematics are built up non-arbitrarily through [conscious] acts of abstraction, idealization, reflection ... Just as the ‘realism’ about physical objects is not a naïve realism, so this unique kind of Platonism about mathematical objects is not a naïve Platonism.”¹⁵⁶ But one can ask, isn’t this still mind-dependent idealism unless the “transcendental ego” is something outside of humans.

In “Mind-independence and mind-dependence in formulations of mathematical realism,” the fourth section of his analysis, Rick seeks to “arrive at an explicit formulation of how a form of mathematical realism might be compatible with transcendental phenomenological idealism.” He returns to Husserl’s position that we can only understand Platonic objects by reflecting on our own thinking processes. Like Husserl, he finds that we cannot go “outside” of ourselves to comprehend them. Thus, “the only way to solve the problem of how we can be related to transcendent (or mind-independent) objects is from within the phenomenological reduction. Once we restrict ourselves to the sphere of appearances, to what is immanent, on the basis of the epoché, we see that consciousness exhibits intentionality.”¹⁵⁷

Here, Rick and Husserl touch on the key question for Platonism: *how can a non-spatiotemporal object interact with objects in the spatiotemporal universe?* The interaction may be physical instantiation or mental perception. Although the answer

¹⁵⁶ Ibid.

¹⁵⁷ Ibid., 19.

suggested in this thesis is different than Rick's, the question is certainly the same.

In "Compatibility or Incompatibility," Rick evaluates current "conceptions of ... mind-independent and mind-dependent, the immanent and transcendent, and appearance and reality" from a "phenomenological reductionist" perspective. Assuming that "appearances ... immanent and mind-dependent" are different than the "appearance-independent reality or the transcendent as mind-independent," Rick finds that "intentional ... consciousness" directed toward mathematics is not constrained by sensory input but is by formal structures ("grammatical, formal, meaning-theoretic," etc.). "Some things appear to us as immanent, some as transcendent."¹⁵⁸

In a diagram, Rick represents "mind-dependent₁" objects on one side opposite "mind-independent₁" objects on the other. In this opposition, it appears that "mathematical realism and mathematical idealism are incompatible," mathematical objects are one or the other but not both. However, Rick posits a second layer beneath mind-dependent₁ objects: "mind-dependent₂" and "mind-independent₂." In this scheme, mathematical objects may be both "mind-dependent₁" and "mind-independent₂." As ultimately mind-dependent objects, they are certainly "compatible with transcendental phenomenological idealism."¹⁵⁹

For Rick, these objects of "constituted mathematical realism or constituted Platonism" are the subjects of "non-arbitrary ... or rationally motivated constituted mind-

¹⁵⁸ Ibid. 23.

¹⁵⁹ Ibid. 23-24.

independence.”¹⁶⁰ As Kant bridged the gulf between *a priori* and *a posteriori* with “synthetic a priori,” Rick crosses the divide between mathematical realism and idealism. But what mathematical objects are “mind-dependent₁” and truly “mind-independent₂?”

Turning to the “constitution of the sense of mind-independence from within the epoche,”¹⁶¹ Rick takes us back inside the mind to consider the “sense of existence of the ideal mind-independent mathematical objects,”¹⁶² asking us to consider our epoche-internal impressions of what we think of or “sense” as “external” objects. In view of his distinctions, Rick tells us that the “assertion that mathematical objects are mind-independent is naïve (or precritical) mathematical realism and is untenable.” But is it? Defining “mind-independence” as an internal function brings us back to idealism.

Rick favors the “combin[ation of] transcendental phenomenological idealism and a mathematical realism in which neither ... is naïve.” His “constituted Platonism, unlike naïve metaphysical Platonism, does not cut off the possibility of knowledge of mathematical objects.”¹⁶³ But it may claim that they are inside the mind to begin with, not outside it.

Rick notes that although his model of realism is similar to “Hilary Putnam’s ‘internal realism,’” there are important differences. Unlike Putnam’s, Rick’s model may

¹⁶⁰ Ibid. 24.

¹⁶¹ Husserl’s “*epoché* or ‘bracketing’ ... [or] methodological constraint” forces us to frame “any phenomenological description...from a first person point of view.” Beyer, Christian, “Edmund Husserl”, *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, (Stanford: Metaphysics Research Lab, 2008), <http://plato.stanford.edu/archives/fall2008/entries/husserl/> (accessed June 14, 2008)

¹⁶² Tieszen, “Mathematical Realism and Transcendental Phenomenal Realism,” 25.

be “applied [to] mathematical objects or states of affairs.”¹⁶⁴

In “Brief Interlude: Where to Place Gödel, Brouwer, and Other Mathematical Realists and Idealists in Our Schematization,” Rick places Gödel and Brouwer in his diagrammatic scheme. He sees Brouwer as a “naïve idealist” while Gödel had moved beyond “naïve metaphysical Platonism” through Husserl’s transcendental phenomenism toward Rick’s mind-dependent – mind-independent² “constituted Platonism.”

In “Conclusion and an Introduction,” Rick asks “If it is possible ... [for] a form of mathematical realism [to be] compatible with transcendental phenomenological realism ... about which kinds of mathematical objects and states of affairs ... can we be constituted realists?”¹⁶⁵ At this point, Rick calls for “constitutional analysis ... [that] Husserl would hold that natural numbers and the geometric objects of Euclidean geometry could in principle be constituted as particular objects.” Beyond Husserlian implication, Rick finds “many questions” including “whether it is possible to constitute generalities about mathematical objects even if we cannot constitute such objects individually ... [and more generally] could there even be a kind of objectivity in mathematics without objects?”¹⁶⁶

Rick asks questions about mathematical objects that are possible but not

¹⁶³ Ibid. 26.

¹⁶⁴ Ibid., 27–28.

¹⁶⁵ Ibid., 28.

¹⁶⁶ Ibid., 29.

conceivable in a detailed way. In his “constituted Platonism,” these objects are mind-independent and real from within the epoche of a mind. Are they real outside the epoche?

For many who see an unbridgeable gap between Platonic-mathematically real objects and the material world, Rick’s approach offers a new way to focus onto the consciously knowable. For the “naïve metaphysical Platonist,” another approach is needed.

Physical Platonism

Only a few physicists have advocated Platonism but their number includes key founders of Quantum Mechanics, a pioneer in mathematical logic, and a leading contemporary mathematical physicist. This section provides a brief overview of their Platonic positions.¹⁶⁷

Paul Dirac

Famous for elaborating the wave-particle duality theory, Paul Dirac (d. 1984) believed that physical phenomena and laws are fundamentally defined by aesthetically “beautiful” mathematics. Like many other physicists, Dirac relied upon a sense of mathematical beauty as a filter, to determine which mathematical structures were employed in his physics. The process worked in the other direction, deduction from beautiful mathematical structures would lead to the discovery of correlated physical

¹⁶⁷ Because I found more Platonism in Roger Penrose’s works than those of other physicists, this section presents a large discussion of his theories.

entities.¹⁶⁸

Reviewing the changes in quantum theory, in 1954, he noted, “With all the violent changes to which physical theory is subjected in modern times, there is just one rock which weathers every storm, to which one can always hold fast—the assumption that the fundamental laws of nature correspond to a beautiful mathematical theory.”¹⁶⁹

Werner Heisenberg

Commenting on Dirac’s discovery of antimatter (positron), Werner Heisenberg (d. 1976) remarked, “For any particle, with pair-production creating particles from energy, the number and configuration of particles of which it consists is indeterminate, so long as the total symmetry of the system is the same as the symmetry of the particle ... [thus] the elementary particle is not elementary anymore. It is actually a compound system, rather a complicated many-body system ... the fundamental structures of nature are much more abstract than we had hoped for.”¹⁷⁰ Later, commenting again on Dirac’s work, Heisenberg remarked: “The particles of modern physics are representations of symmetry

¹⁶⁸ Dirac, quoted in “Pythagorean Heuristic in Physics,” by Sorin Bangu, *Perspectives on Science* 2006, 14, no. 4 (2006): 401.

¹⁶⁹ Dirac wrote, “fundamental problems in theoretical physics....relativistic formulation of quantum mechanics and the nature of quantum nuclei ... will ... require ... drastic revision of our fundamental concepts....so great that it will be beyond the power of human intelligence to get the necessary new ideas by direct attempts to formulate the experimental data in mathematical terms....therefore [physicists will] have to proceed in a more indirect way....to employ all the resources of pure mathematics in attempts to perfect and generalize the mathematical formalism that forms the existing basis of theoretical physics, and after each success in this direction, to try to interpret the new mathematical features in terms of physical entities.” *Ibid.*, 388.

¹⁷⁰ Heisenberg, Werner, *Encounters with Einstein* (Princeton: Princeton University Press, 1983), 32.

groups and to that extent they resemble the symmetrical bodies of Plato's philosophy."¹⁷¹

By 1958, he had unambiguously affirmed a Platonic view of quantum reality, "I think that modern physics has definitely decided in favor of Plato. In fact, the smallest units of matter are not physical objects in the ordinary sense; they are forms, ideas which can be expressed unambiguously only in mathematical language ... mathematical forms that represent the elementary particles will be solutions of some eternal law of motion for matter."¹⁷²

Kurt Gödel

In a 1962 response to questions by Leon Rappaport, who had asked if the Incompleteness Theorems implied that some physical phenomenon predicted by mathematics could be undecidable, Kurt Gödel (d. 1978), a mathematical Platonist, replied positively. "If the mathematical problems involved in the derivation of individual phenomena from the laws of physics are sufficiently complicated, specific physical

¹⁷¹ Heisenberg, Werner, "The Nature of Elementary Particles," in *Interpreting Bodies: Classical and Quantum Objects in Quantum Physics*. Ed. E. Castellani (Princeton: Princeton University Press, 1998), 219.

¹⁷² "I think that modern physics has definitely decided in favor of Plato. In fact, the smallest units of matter are not physical objects in the ordinary sense; they are forms, ideas which can be expressed unambiguously only in mathematical language....The elementary particles in Plato's *Timaeus* are finally not substance but mathematical forms. 'All things are numbers'" is ...attributed to Pythagoras. The only mathematical forms available at that time were ... geometric forms ... regular solids or the triangles which form their surface. In modern quantum theory there can be no doubt that the elementary particles will finally also be mathematical forms but of a much more complicated nature. The Greek philosophers thought of static forms and found them in the regular solids. Modern science....has from its beginning ...started from the dynamic problem. The constant element in physics since Newton is not a configuration or a geometrical form, but a dynamic law. The equation of motion holds at all times, it is in this sense eternal, whereas the geometrical forms, like the orbits, are changing. Therefore, the *mathematical forms that represent the elementary particles will be solutions of some eternal law of motion for matter*. This is a problem which has not yet been solved." Werner Heisenberg, *Physics and Philosophy: The Revolution in Modern Science* (New York: Harper and Row, 1958), 71-72.

questions (such as the occurrence or non-occurrence of a phenomenon under specific conditions) can become undecidable. I don't think it has ever been investigated whether the physics of today has reached this degree of complication ... if it has, the same restriction would apply.¹⁷³ Two years later, John Bell published his Inequalities Theorem.

Roger Penrose

Roger Penrose (Mathematical Institute, Oxford University) promotes a Platonism of interdependent mentality, Planck level physicality, and mathematical truth. He presents his view in *The Emperor's New Mind* (1989),¹⁷⁴ *Shadows of the Mind* (1994),¹⁷⁵ and the *Road to Reality* (2004).¹⁷⁶ Speculating about neurophysics as well as theoretical physics, Penrose finds quantum entanglement in many places and Platonism at the Planck level.¹⁷⁷

¹⁷³“It depends on the structure of the physical theory concerned, whether the incompleteness of the systems of mathematics implies the existence of unpredictable physical phenomena. If the mathematical problems involved in the derivation of individual phenomena from the laws of physics are sufficiently complicated, specific physical questions (such as the occurrence or non-occurrence of a phenomenon under specific conditions) can become undecidable. I don't think it has ever been investigated whether the physics of today has reached this degree of complication...if it has, the same restriction would apply that I mentioned about mathematics in the beginning of this letter.” Gödel, Kurt, “Gödel to Rappaport,” in *Collected Works*, Feferman, Solomon Feferman John W. Dawson, Jr., ed. (Oxford: Clarendon Press, 2003), 177.

¹⁷⁴ Roger Penrose, *The Emperor's New Mine, Concerning Computers, Minds and the Laws of Physics* (Oxford: Oxford University Press, 1994).

¹⁷⁵ Roger Penrose, *Shadows of the Mind: A Search for the Missing Science of Consciousness* (Oxford: Oxford University Press, 1994).

¹⁷⁶ Roger Penrose, *The Road to Reality* (London: Alfred A. Knopf, 2004).

¹⁷⁷ Theoretically, the Planck scale includes the smallest unit of size, time, and mass. Thus, the Planck length is 1.6×10^{-35} meters. And, the Planck unit of time is the Planck length divided by the speed of light or 5.4×10^{-44} seconds. For the complete set of Planck scale measures, see Physics, School of University of New South Wales “The Planck Scale,” *Einsteinlight* (2005), http://www.phys.unsw.edu.au/einsteinlight/jw/module6_Planck.htm (accessed May 25, 2008)

Penrose argues that Gödel's incompleteness theorems lead us to a new definition of consciousness as non-algorithmic. Looking for an intra-brain candidate, Penrose suggests an "Orchestrated Objective Reduction" ("Orch OR") mechanism involving quantum gravity and decoherence at the Planck scale. Quantum entangled biological components ("tubulin subunit proteins" within structural microtubules of neurons) carry out computations by interacting within and between neurons.

For Penrose, information at this intra-biological level is Platonic, representing the mathematically true, beautiful, and ethical. He postulates three "worlds: physical, mental, and truth [Platonic mathematical]." Since these early works, several mathematical physicists critically challenged Penrose's quantum-level assumptions.¹⁷⁸ However, Penrose continues to explore the role of Platonism in modern physics and perception.

In the *Road to Reality* (2004), he turns to an overview of contemporary physics. In the process, Penrose argues that contemporary physics assumes that timeless, limitless, active-everywhere conditions and substances (wave functions, entangled systems, Higgs field, mbranes, etc.) underlie existence.¹⁷⁹ He finds "causality violations in which closed timeline curves can occur, and it becomes possible for a signal to be sent from some event into the past of that same event."¹⁸⁰

¹⁷⁸ For example, Max Tegmark (MIT) has shown that the time period postulated by Penrose (and his coauthor Stuart Hameroff) for neuronal triggering and firing in microtubules is at least 100 times slower than the decoherence period. See Tegmark's comments about Penrose's theory in Max Tegmark, "The Mathematical Universe," *Foundations of Physics*, 38, no. 2 (February, 2008), <http://web.ebscohost.com.libaccess.sjlibrary.org/ehost/detail?vid=6&hid=113&sid=9e3bcdd0-80a7-45d0-b231-8e8a69f95a9c%40sessionmgr108> (accessed May 25, 2008)

¹⁷⁹ Penrose, *The Road to Reality, A Complete Guide to the Laws of the Universe*, 508.

¹⁸⁰ *Ibid.*, 409.

Penrose believes that problems in quantum mechanics including nonlocality lead to a philosophical shift among theoreticians.¹⁸¹ Although he believes it will continue to advance, contemporary physical theory does not reach for the “true road to reality ... [Therefore] some new insights are needed.”¹⁸²

He finds mathematical modeling essential to physics, enabling us to adequately represent the physical world and make verifiable predictions. But, it is the ultimate, mathematical objects underlying the equations of models that are Platonically real for Penrose. Restating his three world model, Penrose indicates that “the Platonic world may be the most primitive of the three, since mathematics is a ... necessity, virtually conjuring it’s very self into existence through logic alone.”¹⁸³ In this work, Penrose restates his

¹⁸¹ “I believe that a new perspective is certainly needed and that this change in viewpoint will have to address the profound issues raised by the measurement paradox of quantum mechanics and the related nonlocality that is inherent in EPR effects and the issue of ‘quanglement.’” Penrose, *The Road to Reality, A Complete Guide to the Laws of the Universe*, 1025.

¹⁸² Ibid., 1027.

¹⁸³ “[M]odern physicists invariably describe things in terms of mathematical models ... as though they seek to find ‘reality’ within the Platonic world of mathematical ideals ... then physical reality would appear merely as a reflection of purely mathematical laws ... [but] we are a long way from any such theory.... [However] the more deeply we probe Nature’s secrets, the more profoundly we are driven into Plato’s world of mathematical ideals as we seek our understanding.... At present, we can only see that as a mystery.... But are mathematical notions things that really inhabit a ‘world’ of their own? If so, we seem to have found our ultimate reality to have its home within that entirely abstract world. Some ... have difficulties with accepting Plato’s mathematical world as being in any sense ‘real’ and would gain no comfort from a view that physical reality itself is constructed merely from abstract notions. My own position on this matter is that we should ... take Plato’s world as providing a kind of ‘reality’ to mathematical notions ... but I might baulk at actually attempting to identify physical reality within the abstract reality of Plato’s world...[My three sphere model] expresses my position on this question, where each of three worlds—Platonic-mathematical, physical, and mental—has its own kind of reality, and where each is (deeply and mysteriously) founded in the one that precedes it (the worlds being taken cyclically) ... the Platonic world may be the most primitive of the three, since mathematics is a...necessity, virtually conjuring its very self into existence through logic alone.” Ibid., 1027-1029.

earlier “three worlds and three mysteries” model.¹⁸⁴

These worlds (“spheres”) somehow interact. For Penrose, this is a deeper mystery suggesting a Platonic-like connectivity¹⁸⁵ that explains how and why do the worlds interact cyclically. Truth pushes (shape or form, perhaps) to Physicality which pushes (material of concepts) to Mentality which pushes (observational limits) to Truth.¹⁸⁶

He points out that consciousness-observation is critically important in his model (Mentality) as it is in traditional quantum theory. As he notes, in all expressions of quantum theory, the wave function reduction “R” element (ending the unobserved wave function, the “U” state) depends upon an observer or measurement. In fact, for the Copenhagen interpretation, the wave function exists not independently but only in “the observer’s mind.” One version, in fact, demands an actual “observation” for a wave function to exist.

Penrose finds that another R interpretation, quantum “environmental decoherence,” leads us to an Everette-like multiverse with each state, at collapse, splitting off as a separate universe. For Penrose, this model is incomplete because it lacks “an

¹⁸⁴ Penrose’s three world model consists of: Physicality (The physical corresponds to the observable universe of particle-wave, mass, and field interactions.), Mentality (The mental world corresponds to conscious brain activity.), and Truth (Truth exists as mathematical-Platonic objects at the non-computational level of spacetime geometry and measurement.). Two spheres surround Truth: first Beauty, then Morality. As he notes, “Beauty and Truth are intertwined, the beauty of a physical theory acting as a guide to its correctness in relation to the Physical World, whereas the whole issue of Morality is ultimately dependent upon the World of Mentality.” Penrose, *The Road to Reality, A Complete Guide to the Laws of the Universe*, 1029.

¹⁸⁵ Because his own three world model has a “deep mystery” (cyclicity) for him, perhaps Penrose suggests that the model itself is the reflection of some Platonic entity. Max Tegmark also addresses this issue: where do we set limits on what is or is not “mathematically real?” His criteria is Godelian-like decidable. Tegmark, “The Mathematical Universe,” 1.

¹⁸⁶ Penrose, “Mathematical Realism and Transcendental Phenomenal Realism,” 1029–1030.

adequate theory of observers.” A “consistent histories” model also depends upon an active observer. And, the Wigner view poses consciousness stopping “U” evolution.

Penrose finds that one model of quantum mechanics greatly diminishes or eliminates role of observation: DeBroglie-Bohmian Mechanics which changes R and U factors from observer-dependent to real entities. In Bohmian Mechanics, this change is partly effected by the existence of deterministic “hidden variables” (“pilot wave” or “guiding equation”).¹⁸⁷ Penrose’s own gravitational model also converts the R into an objective entity. In his model, the presence of gravity replaces the observer (or measurement) as the reduction agent. He switches the causal roles of the R process and consciousness. Instead of the classical quantum perspective in which an observer causes R, the existence of R partly causes the conscious observer to exist. Although he reverses these roles, like his predecessors, Penrose continues to include conscious observation in the model of objective reality.

Penrose explains that his model associates consciousness with a quantum coherence (among proteins in microtubules) including much of the brain, similarly to object-wide superconductivity in a substance. Asking if an experimental test is possible for his model, Penrose remarks that it is analogous to the “binding problem” observed in conscious perception involving the activity of multiple brain centers combining to form an image. He points to Andrew Duggins who suggested that one could experimentally determine whether conscious image formation violates Bell’s Inequalities with a brain

¹⁸⁷ Ibid., 1031- 33.

area-wide EPR nonlocality.¹⁸⁸ Summarizing these earlier models, Penrose asserts that a “fundamental physical theory that lays claim to any kind of completeness at the deepest levels of physical phenomenon must have the potential to accommodate conscious mentality.”¹⁸⁹ He rejects “computational functionalism,” referring again to Gödel’s theorems (and Turing’s) as support for the irreducibility of conscious mental activity to brain computation.

Roger Penrose notes that entanglement is involved in quantum measurement. “For all practical purposes,”¹⁹⁰ he finds a philosophical “environmental decoherence” approach common among theoretical physicists. Under his interpretation, “the state reduction R [wave function collapse] can be understood as coming about because the quantum system under consideration becomes inextricably entangled with its environment.”¹⁹¹

Turning to the “mathematical road to reality,” Penrose comments that a new theory for physical reality “must differ enormously” from previous theories. Whatever the nature of the new theory, it should recognize the “deep unity between certain areas of mathematics [but not all] and the physical world.”¹⁹² Discoveries of real numbers, multiple geometries (Euclidean and non-Euclidean), integral and differential calculus,

¹⁸⁸ Ibid., 1033.

¹⁸⁹ Ibid.

¹⁹⁰ Penrose adopts John Bell’s phrase “for all practical purposes (FAPP)” referring descriptions of physical reality in terms of mathematical density matrices. Penrose, *The Road to Reality, A Complete Guide to the Laws of the Universe*, 802.

¹⁹¹ Ibid, 528.

differential equations, and other mathematical formulations enabled theoretical and experimental physics to advance. Penrose believes that our current understanding of the physical world importantly depends upon two elements of mathematics: complex numbers and symmetry.

Complex numbers (applied in complex analysis, complex matrix formulation, complex polynomials, and complex Lie algebra) are “magically” basic to quantum mechanics and associated areas of theoretical physics.¹⁹³ However, Penrose notes that the complex numbers (the “holomorphicity” expressed in complex analytics) of quantum expressions is conveniently reduced to real numbers when “quantum information,” present in entangled states, is broken at measurement.¹⁹⁴ Perhaps, Penrose remarks, “we should seek a role for discrete combinatorial principles ... emerging out of complex magic, so spacetime should have a discrete underlying structure rather than a real number based one ... [I] believe[s] that there are deep matters of importance here, concerning the very mathematical basis of physical reality.”¹⁹⁵

¹⁹² Ibid. 1034.

¹⁹³ “Complex numbers are fundamental to the operations of quantum mechanics, as opposed to real numbers which provided the foundation of ... successful previous theories... There is something of a mystery, needing some kind of explanation, why the role of these numbers should appear to be so universal in the framework of quantum theory, underlying ... quantum superposition... and in a different guise, the Schrodinger equation, the positive-frequency conditions, and the infinite-dimensional ‘complex structure’ ... in quantum field theory.” Ibid. 1033–34.

¹⁹⁴ “Even the standard formalism of quantum mechanics, although based on complex numbers, is not an entirely holomorphic theory ... [seen] in the requirement that quantum observables be described by Hermitian operators and in the unitary nature of quantum evolution... The Hermitian property has to do with the ... demand that the results of measurements be real numbers, and the unitarity, that ‘probability be conserved ... whereby a complex amplitude is converted to a probability.” Ibid. 1035.

¹⁹⁵ Ibid., 1036.

Symmetry is also basic to physical theory. Penrose notes that relativity theory, quantum mechanics, and particle theories centrally involve symmetry.¹⁹⁶ In fact, “there are circumstances where an exact symmetry group can come about even with structures where no symmetry is initially imposed.”¹⁹⁷ Pointing to the “mysterious number constants of Nature,” Penrose restates the popular view that they could have appeared as symmetry-breaking when the early universe expanded. Finding other symmetric issues in nature, he mentions the “chiral asymmetry of weak interactions,” and “time-asymmetry.”¹⁹⁸

When Penrose turns to “beauty and miracles,” he addresses a “mysterious aspect of mathematics...that underlies physical theory at its deepest level.”¹⁹⁹ These two “driving forces” significantly direct much physical research. He finds that many highly successful physical theories including Newtonian mechanics, equations of Maxwell’s electromagnetic theory, Dirac’s wave equations, and Einstein’s special and general relativity²⁰⁰ are expressed by beautiful mathematical structures.

This reflection leads to the question, “How much of the Platonic mathematical world lies at the base of the arrow that depicts the ‘first mystery’ [Physicality]?”²⁰¹ Then, Penrose asks if we can identify, in advance, mathematics that governs activity in the

¹⁹⁶ Ibid.

¹⁹⁷ Ibid., 1037.

¹⁹⁸ Ibid., 1037- 38.

¹⁹⁹ Ibid., 1038.

²⁰⁰ Ibid., 1038- 39.

physical world? I agree that this is an important question. If we can reduce the similarities or typologies in previously useful mathematical formulations to one or a group of abstract expressions, we may be able to use those expressions to predict new trends in physics.

As “miracles,” Penrose mentions several examples where unanticipated mathematical developments led to miraculous simplifications in modern physical theories (e.g., multiple string theories to Ed Witten’s unification statement).

Julian Barbour

Julian Barbour, a widely-published theoretical physicist, argues for a timeless “Platonia” that blends the requirements of GR (including the configuration of spacetime geometry by matter and QM (including Everett’s Many Worlds) with a Platonic universe of form-like things.²⁰² In his scheme, a “horizontal causality” (pre- or atemporal settings) must replace the popular “vertical causality” (causal chains extending into the past). “Platonia as a whole determines how the static wave function ‘beds down’ on its landscape.”²⁰³

Max Tegmark

Mathematical physicist Max Tegmark (Physics Department, MIT) proposes a detailed model of a Platonic-like mathematical reality that encompasses the physical

²⁰¹ Ibid., 1039.

²⁰² Barbour, Julian, *The End of Time* (New York: Oxford University Press, 1999).

²⁰³ Ibid., 311-313.

world. In “The Mathematical Universe,” he argues based upon three hypotheses:

- 1) “External Reality Hypothesis (ERH): There exists an external physical reality completely independent of us humans” implies:
- 2) “Mathematical Universe Hypothesis (MUH): Our external reality is a mathematical structure” which further defined by:
- 3) “Computable Universe Hypothesis (CUH): The mathematical structure that is our external physical reality is defined by computable functions.”

Tegmark’s multiverse has four levels:

- “Level 1: Regions Beyond Our Cosmic Horizon: Same laws of physics, different initial conditions” which assumes “infinite space, ergodic²⁰⁴ matter distribution.” The evidence for this level is “microwave background measurements point[ing] to flat, infinite space [with] large-scale smoothness. [This is the] simplest model [of the universe].”
- “Level 2: Other Post-Inflation Bubbles: Same fundamental equations of physics, but perhaps different constants,²⁰⁵ particles and dimensionality” which assumes that “chaotic inflation occurred.” The evidence for this level is that “inflation theory explains flat space, scale-invariant fluctuations, solves the horizon problem ... explains the fine-tuned

²⁰⁴ The initial conditions do not affect the overall stochastic pattern of the process. See Eric C Weisstein, “Ergodic Theory,” *Wolfram MathWorld* (2008), <http://mathworld.wolfram.com/ErgodicTheory.html> (accessed September 10, 2008)

²⁰⁵ For example, the Fine Structure Constant which determines the interactive force of electromagnetic attraction/repulsion could have a different constant value.

parameters [of nature].”

- “Level 3: The Many Worlds of Quantum Physics: Same features as level 2.” Assume that “physics [is] unitary.” The evidence appears in “experimental support for unitary physics [including] quantum gravity, decoherence [is] experimentally verified.” This is the “mathematically simplest model.”
- “Level 4: Other Mathematical Structures: [with] different fundamental equations of physics.” This level assumes that “mathematical existence = physical existence.” The evidence is apparent in “unreasonable effectiveness of math in physics.” It “answers the Wheeler/Hawking question: ‘why these equations [of physics], not others.’”²⁰⁶

Tegmark’s Level 4 corresponds to a blend of mathematical and physical Platonism. Accepting his MUH-CUH perspective, eliminates significantly blocking questions for physical Platonism such as “how can a Platonic entity interact with the physical world?” and the related “how can a Platonic form be instantiated in the physical world?”

Tegmark writes “I have suggested that ... mathematical existence and physical existence are equivalent, so that all mathematical structures have the same ontological status. This can be viewed as a radical Platonism, asserting that the mathematical structures in Plato’s realm of ideas ... exist ‘out there’ in a physical sense, casting the

²⁰⁶Tegmark, “The Mathematical Universe,” 1, 14 - 16, 19 - 20, and 27.

modal realism theory of David Lewis²⁰⁷ in mathematical terms akin to what Barrow refers to as ‘ π in the sky.’”²⁰⁸ This multiverse “has no free parameters, all properties of all parallel universes ... could in principle be derived by an infinitely intelligent mathematician.” In fact, “MUH says that a mathematical structure is our external physical reality, rather than being merely a description thereof” and “the point is not that a mathematical structure describes a universe, but that it is a universe.” Tegmark’s system includes self-conscious beings that are unaware that they are mathematical structures, “this equivalence between physical and mathematical existence means that if a mathematical structure contains a SAS [“self-aware substructure” such as a mind], it will perceive itself as existing in a physically real world, just as we do.”²⁰⁹

Defining “mathematical structure,” Tegmark takes a Hilbert-like approach, “all mathematical structures are just special cases of one and the same thing: so-called formal systems. A formal system consists of abstract symbols and rules for manipulating them, specifying how new strings of symbols referred to as theorems can be derived from given ones referred to as axioms.” He includes General Relativity and Quantum Field Theory among these formal systems, the former derived from differential operators, manifold tensor fields, and metric manifolds. The latter are derived from differential operators,

²⁰⁷ “We ought to believe in other possible worlds and individuals because systematic philosophy goes more smoothly in many ways if we do; the reason parallels the mathematicians’ reason for believing in the set-theoretical universe. By ‘other worlds’ I mean other things of a kind with the world we are part of: concrete particulars, unified by spatiotemporal unification or something analogous, sufficient in number and variety to satisfy a principle to the effect, roughly, that anything can coexist with anything.” David Lewis, *On the Plurality of Worlds* (London: Blackwell, 1986), 1.

²⁰⁸ See J.D. Barrow, *Pi in the Sky* (Clarendon: Oxford, 1992).

²⁰⁹ Tegmark, “The Mathematical Universe.”²⁰

linear operators, and Hilbert spaces. He notes that most theoretical physicists assume that “some mathematical structure[s are] isomorphic to the physical world, with each physical entity having a unique counterpart in the mathematical structure and vice versa.”²¹⁰

Mark Balaguer (Philosophy Department, California State University Los Angeles) notes the ever-present problem of Platonism: “The problem is that mathematical Platonism seems to make mathematical knowledge impossible, because even if there did exist such things as abstract mathematical objects, they would be causally isolated from us, and so it would be impossible for us to have any *information-transferring contact* with them.”²¹¹ Max Tegmark claims to solve this problem. He argues that the step from MUH to CUH, expressed in Level 4, equates mathematical realism and physical realism. At this highest level of abstraction, there is no difference between the two; physical structures are just forms of mathematical structures. For Tegmark, the question “how do minds perceive or contact these ‘real’ objects?” may be a pointless. As validly as we ordinarily relate to “physical objects,” we intuit (a la’ Gödel) mathematical objects.

Others

Others have noted the prevalence of Platonism among theoretical physicists. One, Shahn Majid (Mathematics Department, Queen Mary College, University of London) works on quantum group theory. In a recent posting, Majid notes, “In mathematics you

²¹⁰ Ibid.

²¹¹ Mark Balaguer, “Can We Know that Platonism is True?” reviewing *Realist Rationalism* by Jerry Katz in *The Philosophical Forum*, 34, nos. 3 and 4, (Fall/Winter 2003), <http://www.blackwell-synergy.com/doi/abs/10.1111/1467-9191.00152>.

have the notion of a structure and a representation of it ... you could say that the set of representations was the reality ... Physics is the quest for reality, the construction of representations of those bits of reality, the realization that those representations themselves are reality, and then unification to a new object.... Our system of knowledge is organized in a hierarchy, where we have more and more assumptions [when we are aware of these assumptions] we are behaving like mathematicians and we are exploring their consequences, and to the extent that we are not aware of them, we are behaving like physicists and are living in that world.”²¹²

Jordi Cat (Department of History and Philosophy of Science, Indiana University) recently reviewing *Symmetries in Physics: Philosophical Reflections*, edited by K. Brading and E. Castellani, reports on Platonic-like attitudes among some mathematical physicists contributing to the volume. Some, he notes, find that “symmetry principles ‘dictate the very existence of all known forces of nature.’” And, some contributing physicists acknowledge “a mysterious, even mystical, Platonist-Pythagorean role for purely mathematical physics in theoretical physics.”²¹³

²¹² Shahn Majid, *Faces of Mathematics*, <http://www.ma.hw.ac.uk/~ndg/fom/majidqu.html> (accessed June 22, 2008)

²¹³ In this review, Jordi Cat reports on the Platonism of theoretical physicists but he does not personally advocate Platonism. “Chris Martin’s article elaborates historically and philosophically on this issue on two related fronts, scientific and philosophical, of the gauge argument. The first ... extends between Steven Weinberg’s (also C. N. Yang’s) two well-known methodological banners: the more historical is that twentieth-century physics is the century of symmetries and the *more Platonic* with more ... hubris, is that *symmetry principles ‘dictate the very existence of all known forces of nature.’* ... The price of this move ... is mysterious, even mystical, *Platonist-Pythagorean role for purely mathematical physics in theoretical physics.* [my italics]” Cat, Jordi, “Essay Review: Symmetries in Physics,” *Philosophy of Science*, 73 (October 2006), <http://www.journals.uchicago.edu/doi/pdf/10.1086/516808> (accessed June 15, 2008)

Demonstrated Physical Platonism

Interestingly, some observed quantum-level phenomena mimic certain Platonic characteristics. For example, some mimic the basic “changelessness” of nature proclaimed by Parmenides and “proven” in Zeno paradoxes, described by Plato in the *Parmenides*. A quantum corollary was first suggested in 1932 by Von Neumann. He theoretically proved that any quantum state ϕ could be forced into another state ψ in Hilbert space by rapid measurements. Quantum evolution in time could be stopped by constantly monitoring a system. Forty years later, the effect was formulated mathematically.²¹⁴ A constantly observed quantum state does not change.

The effect occurs when a change from one quantum state to another is stopped by an interaction (random thermal energy, observation, etc.) that causes the last state to be a “transition [that] has not yet occurred ... [or, equally] a transition already occurred.” According to the theory, the continuously observed unstable particle cannot decay.

Each measurement causes the particle wave function to collapse to the eigenstate of the base measurement. Frequent-enough measurements (any outside interaction with the system) can be timed so that it prevents the particle from changing states. The change could take several different forms: a particle moving from one half-space to another, a photon moving within a waveguide from one mode to another, or an entire atom raising or lowering to a different quantum state. Theoretically, the Zeno effect could be extended to macroscopic, humanly visible levels but the apparatus and energy needed for the

observations would be enormous.

The Zeno Effect could be detected when the quantum system (being measured) is strongly coupled to a local environment has a large source of random thermal energy. Under these conditions, with a low amount of decoherence, the wave function collapse time is short.

In 1989, Itano, Heinzen, Bollinger, and Wineland (National Institute of Standards and Technology) physically demonstrated the Quantum Zeno Effect by suppressing change in a quantum system through coupling with a “hot” environment. In the experiment, Beryllium⁺ ions were stored at the low temperature of 250mK. A radio frequency pulse was applied to the container of Be ions. Ordinarily, the pulse would excite the collection. However, the collection was immediately subject to regular ultraviolet pulses. These “measurements” prevented the collection from rising to an excited (higher energy level) state. Like Zeno’s arrow that does not move during an instant (multiplied by an infinite number of instants yields no motion), the collection of Be⁺ ions does not change, as it ordinarily would.²¹⁵ Since then, other experiments have verified the effect.²¹⁶

On the other hand, in 2000, Gershon Kuriki of the Weizmann Institute claimed to

²¹⁴ “For almost all times t , if a particle is continually observed to determine whether it stays in ϵ , then the probability of an affirmative answer is the same as the probability that the particle was in ϵ initially.” K. Gustafson, “Bell and Zeno,” *International Journal of Theoretical Physics*, 44, no. 11 (2005): 1.

²¹⁵ W. M. Itano; D. J. Heinzen, D. J. Wineland, “Quantum Zeno Effect,” *Physical Review*, no. 51 (1990), http://prola.aps.org/abstract/PRA/v41/i5/p2295_1 (accessed February 2, 2008)

²¹⁶ D. Kouznetsov; H. Oberst, “Reflections of Waves from a Ridged Surface and the Zeno Effect,” *Optical Review*, no. 12 (2005).

have proven that the freeze-action effect of the Quantum Zeno Effect should not ordinarily occur in nature. They noted that every particle decay process has a “memory time ... the period in which ... radiation has not yet escaped from an atom [for example], allowing the system to ‘remember’ its state prior to decay.” The memory time in the decay of an excited atom is so short that “freezing” observations would have to be “less than one billionth of a billionth of a second.” Kurki and Kofman found that observations at this rate would impart so much energy to the system that new particles would be created. Then, questions about a Zeno Effect of the former system (which no longer existed) would be moot. In fact, notes Kuriki, these observations would have an *anti-Zeno effect*.²¹⁷

In a recent article denying the possibility of the Zeno Effect, David Atkinson compared the outcome of an infinite number of rigid spherical bodies colliding in classical, relativistic, and quantum mechanics. He found momentum is conserved in classical theory, momentum and energy not conserved in relativistic theory, and that incoherence excludes a Zeno Effect when the set of colliding objects is observed.²¹⁸

Although there is no decision on the Quantum Zeno Effect, the debate about it indicates that Platonism may continue to intrigue is physically as well as philosophically.

²¹⁷ "If we make the analogy between an object undergoing changes in time, for example a decaying nucleus or an excited atom, and Zeno's moving arrow, the arrow will increase its speed as the rate of the 'glimpses' increases. The surprising conclusion of this research is that the anti-Zeno effect (i.e., the increase of decay through frequent observations) can occur in all processes of decay, while the original Zeno effect, which would slow down and even stop decay, requires conditions that only rarely exist in such processes." Gershon Kurizki "Zeno's Paradox Reversed: Watching a Flying Arrow Increase Its Speed" *Science News* (June 5, 2000), <http://www.sciencedaily.com/releases/2000/06/000602074805.htm> (accessed June 16, 2008)

²¹⁸ D. Atkinson, "Losing Energy in Classical, Relativistic, and Quantum Mechanics," *Studies in History and Philosophy of Modern Physics*, 38, no. 1 (March 2007): 12.

Platonism and Information

This thesis introduces “Information Platonism,” combining a “full-blooded Platonism” content suggested by some mathematical realists, aspects of the Platonism advocated by a few physicists (notably, Tegmark and Penrose), and the suggestion that quantum level phenomena can be understood from an information-theoretic perspective. This single universe, not multiverse,²¹⁹ model postulates that the total information of all quantum systems (at all times) is present within the Platonic realm and that some is instantiated in each wave function collapse. For more about this proposal, see the Part “Information Platonism,” in this thesis.

²¹⁹ Multiverse Platonic models (for example, Everett’s with a new universes spawned at each wave function collapse) are obviously possible with the Platonic realm outside the spacetime of all universes. For simplicity, this thesis focuses on a single universe model.

Part Three: Quantum Theory and Information

Overview

This part discusses the relationship between quantum theory and information, introducing the new field of Quantum Information Theory. Applying some of these concepts will enable us to express quantum phenomena in terms of information. Later, we connect information and Platonism, crossing the divide between quantum-level phenomena and the Platonic realm.

Black Holes and Information

Stephen Hawking (Lucasian Professor of Mathematics, University of Cambridge) predicted that black holes dissipate radiation (later verified as bursts of gamma radiation, for example) leading to a reduction of the black hole mass. If the rate of gravitationally-accreted matter does not equal the outgoing “Hawking Radiation,” the black hole will eventually cease to exist. Hawking noted that the outgoing radiation did not contain all of the black hole information, some would be lost. Thirty years after postulating the black hole information loss, Hawking reversed himself, announcing to a theoretical physics conference that the missing information “existed” in parallel universes. He adapted Everett’s multiple universe theory to explain the apparent contravention of the Conservation of Information.

Searching for an alternative to the information loss indicated by the Hawking Paradox that was consistent with equations describing black holes, Leonard Susskind

(Physics Department, Stanford University) found a solution.²²⁰ He showed that total amount of bit information²²¹ attracted into the black hole is expressed on its event horizon. In this holographic-like scheme, three-dimensional information in the black hole is expressed two-dimensionally around the rim of the horizon. And, the bit information of black hole did not diminish as the black hole contracted through Hawking radiation. Focusing on the conservation of information, some theoretical physicists including Susskind have established precedents for conceptualizing quantum-level phenomena in terms of information.

Quantum Information Theory

Traditional information theory²²² focused on the mathematical and theoretical engineering limits of communications. Exploring the “‘fundamental problem of communication,’ reproducing at one point either exactly or approximately a message selected at another point,”²²³ the theory developed a “mind-independent” model of information that “leaves to others [determining] what (how) meaning or content [is]

²²⁰ Leonard Susskind, *Introduction to Black Holes, Information, and the String Theory Revolution: the Holographic Universe* (Singapore: World Scientific Publishing Company, 2004).

²²¹ Like other quantum theorists, Susskind firmly advocates the conservation of information.

²²² Based on the work of Claude Shannon, H. Nyquist, R. Hartley, Norbert Wiener, Boltzmann, Leo Szilard, David McKay, and others.

²²³ “Information Theory,” *The Cambridge Dictionary of Philosophy*, Second Edition, ed. Audi, Robert, (Cambridge: Cambridge University press, 1999), 435.

associated with a message.”²²⁴ Mathematically, the theory examined the quantitative factors of communication. As David McKay indicates, the theory involves simple quantification, “The Shannon information content ... measured in bits ... [is] a natural measure of the [total] information content of [an] event.”²²⁵

Mathematician Claude Shannon²²⁶ noted an indirect relationship between information content and systemic randomness. Thus, he defined “information entropy”²²⁷ as the “uncertainly associated with a random variable.” He also expressed total information content in terms of bits.²²⁸ The pioneering work of Shannon and other information theorists was adapted to quantum mechanics, producing a new field: Quantum Information Theory (QIT).

²²⁴ “Since information is objective, it can generate what we want from knowledge.... In its semantic dimension, information can have intentionality or aboutness. What is happening at one place ... can carry information about what is happening at another place.... The amount of information associated with an event is related to the objective probability of the event. Events that are less likely to occur generate more information than those more likely to occur... A surprising consequence of associating amounts of information with objective likelihoods of events is that some events generate no information. [For example] that $5^5 = 3125$ or that water freezes at 0 deg C. generates no information ... [because] these things cannot be otherwise ... their probability of being otherwise is zero. Thus, they generate zero information.” Ibid, 436.

²²⁵ David McKay, *Information Theory, Inference, and Learning Algorithms*.(2003), <http://www.cs.iastate.edu/~honaavar/infotheorybook.pdf> (accessed August 1, 2008)

²²⁶ Claude E. Shannon, “A Mathematical Theory of Communication,” *Bell System Technical Journal*, no. 27 (July, October, 1948): 379-423, 623-656.

²²⁷ Shannon’s entropy has been challenged as a practical unit of measurement for QM. These attempts have been disproven. For example, see Christopher G. Timpson, “The Application of Shannon Information in Quantum Mechanics and Zelliger’s Foundation Principle,” *Philosophy of Science* 70, no. 5 (December 2003), <http://web.ebscohost.com.libaccess.sjlibrary.org/ehost/detail?vid=5&hid=115&sid=37df67b2-0fe9-4b37-a063-cf61f40e2830%40sessionmgr104> (accessed August 1, 2008)

²²⁸ Wikipedia, “Information Entropy,” http://en.wikipedia.org/wiki/Information_entropy (accessed August 1, 2008)

Emergence of Quantum Information Theory

John Wheeler (d. Physics Department, University of Texas) famously wrote that the “‘It from bit’ symbolizes the idea that every item of the physical world has at bottom an immaterial source and explanation, that what we call reality arises in the last analysis from the posing of yes-no questions and the registering of equipment-evoked responses. In short, he argued that physical things are information-theoretic in origin.”²²⁹ Accepting Wheeler’s observation, we are only a short conceptual step from physical Information Platonism.

In 1961, Rolf Landauer, an IBM physicist, discovered an information analog of the second law of thermodynamics. He found that an elimination of information generated a release of energy, increasing to total entropy in the local environment.

Recently, Leonard Susskind (Physics Department, Stanford University) extended Shannon’s earlier definition to the information of physical systems. He argues that the information of a system involves the total possible knowledge of that system expressed as “maximum entropy.”²³⁰

²²⁹ John Wheeler, “Information, Physics, Quantum: The Search for Links,” in *Feynman and Computation*, ed. J.G.Hey (Reading: Persus Books, 1999), 311.

²³⁰ “In quantum mechanics, the conservation of information is expressed as the unitarity of the S-matrix... [However] a *more refined definition of information is provided by the concept of entropy*. ... [E]ntropy is *not a property of a given system but involves one’s knowledge of the system* [my italics]. To define entropy, we begin with restrictions that express what we know...angular momentum and whatever else we know. The entropy is ... the logarithm of the number of quantum states that satisfy the given restrictions [known knowledge]. ... The maximum entropy is a property of the system. It is the logarithm of the total number of [quantum] states.... It is the entropy given that we know nothing about the state of the system. ... Consider[ing] a [black hole] system that includes gravity...spacetime will be four-dimensional... [Here,] the maximum entropy of a region of space is proportional to its area measured in Planck units.” Susskind, 102.-103.

In order to present the hidden variables explanation for quantum nonlocal entanglement as Platonic information, this thesis introduces Quantum Information Theory (QIT) as example of one way to interpret QM as information and adapts some QIT concepts²³¹ in a scheme of Platonic information.

Quantum Information Theory: Opportunities and Limits

Rob Clifton (Philosophy Department, University of Pittsburg), Jeffrey Bub (Philosophy Department, University of Maryland), and Hans Halvorson (Philosophy Department, Princeton University) interpret quantum mechanics in information-theoretic terms.²³² Clifton, Bub, and Halvorson (CBH) defined “information as ... information in the physical sense, measured ... in the quantum world by the von Neumann entropy.”²³³

They argue that the observable-measurable “state space” characteristics of a quantum system can be expressed as the result of three restraints on information: 1) “impossibility of superluminal information transfer between two physical systems by performing measurement on one of them,” 2) “impossibility of perfectly broadcasting the

²³¹ Because the CBH interpretation of QIT views QIT-modified QM as complete, excluding Bohmian-like pilot waves or similar “extraneous” causal factors, I am only adopting QIT concepts that can be consistently applied to this metaphysical thesis. QIT is fine but it is not Platonic.

²³² Rob Clifton, Jeffrey Bub, and Hans Halvorson, “Characterizing Quantum Theory in Terms of Information-theoretic Constraints,” *Foundations of Physics* 33, no. 11 (April 2003), <http://web.ebscohost.com.libaccess.sjlibrary.org/ehost/pdf?vid=3&hid=21&sid=f13271bc-b3ae-4cc4-8422-32eb0e046bda%40sessionmgr2>. (accessed August 1, 2008)

²³³ Jeffrey Bub, “Quantum Mechanics is About Quantum Information,” *Foundations of Physics* 35, no. 4, (2004), <http://web.ebscohost.com.libaccess.sjlibrary.org/ehost/pdf?vid=17&hid=114&sid=e01d83ab-85bb-4cd8-a667-ca9dd9806b09%40sessionmgr3> (accessed August 1, 2008)

information contained in an unknown physical state,”²³⁴ and 3) “impossibility of unconditionally securing bit commitment.”²³⁵

Applying these narrow restrictions to information in a QM context enables CBH to interpret quantum information as a “physical primitive.” Referring to Einstein’s distinction between “principle” and “constructive” theories,²³⁶ they present QIT as a principle theory, incorporating three information restrictions similarly to Special Relativity (SR), a principle theory that included two key restrictions.²³⁷ CBH argue that their three constraints lead to “physical characteristics of a quantum theory ... [including] the physical world must be nonlocal, in that spacelike separated systems must at least sometimes occupy entangled states.”²³⁸ Similarly to non-QIT QM interpretations, the CBH view accepts particle and system entanglement but it does not “explain” them as other than as a necessary probabilistic correlation.

²³⁴ Clifton, Bub, and Halvorson, “Characterizing Quantum Theory in Terms of Information-theoretic Constraints,” 1562.

²³⁵ “In a bit commitment protocol, Alice supplies an encoded bit to Bob. The information available in the encoding should be insufficient for Bob to ascertain the value of the bit, but sufficient, together with further information supplied by Alice at a subsequent stage when she is supposed to reveal the value of the bit, for Bob to be convinced that the protocol does not allow Alice to cheat by encoding the bit in a way that leaves her free to reveal either 0 or 1 at will.” Ibid.

²³⁶ “According to Einstein, two ...different sorts of theories should be distinguished...One ...involves the reduction of a domain of ...complex phenomena to properties of simpler elements, as in the kinetic theory which reduces the mechanical and thermal behaviour of gases to the motion of molecules, the elementary ...blocks of the constructive theory. The other ...is formulated in terms of ‘no go’ principles that impose constraints on physical processes or events, as in thermodynamics [a principle theory].” Bub, “Quantum Mechanics is About Quantum Information,” 544.

²³⁷ “[E]quivalence of ‘inertial frames for all physical laws...[and] constancy of the velocity of light in vacuo for all inertial frames.” Ibid., 542–544.

²³⁸ Clifton, Bub, and Halvorson, “Characterizing Quantum Theory in Terms of Information-theoretic Constraints,” 1563.

In “Quantum Mechanics is About Quantum Information,” Jeffrey Bub elaborates on the earlier work in CBH. He proposes an “interpretation of quantum mechanics as a theory about the representation and manipulation of information in our world, not a theory about the mechanics of nonclassical waves or particles.”²³⁹ Bub completely rejects Bohmian mechanics (including hidden variables) as unnecessary because it involves an additional, unnecessary factor. [Bohmian mechanics are] “not needed to explain quantum phenomenon given the information-theoretic constraints, such a story [Bohmian] can ... have no excess empirical content over quantum mechanics.”²⁴⁰ In Bub’s view, a QIT explanation of nonlocality should not include hidden variables. If QIT features are adopted for this thesis, they must go beyond Bub’s exclusive view.

Hans Halvorson, one of the three authors of the CBH paper, later finds limits to the three “information-theoretic constraints” theory proposed by CBH. However, he does indicate that quantum information theory (QIT) “provides us with a new perspective from which we can approach traditional questions about the interpretation of quantum mechanics.”²⁴¹

In “Explaining the Unobserved—Why Quantum Mechanics Ain’t Only About

²³⁹ Bub, “Characterizing Quantum Theory in Terms of Information-theoretic Constraints,” 542.

²⁴⁰ Ibid., 543.

²⁴¹ Hans Halvorson, “A note on information theoretic characteristics of physical theories” *Philosophy of Science Archives* (October 15, 2003), <http://philsci-archive.pitt.edu/archive/00001445/> (accessed August 2, 2008)

Information,”²⁴² Amit Hagar (Philosophy Department, University of Delaware) and Meir Hemmo (Philosophy Department, University of Haifa) find significant deficiencies in the CBH argument including its inability to account for the quantum measurement problem.²⁴³ They “criticize Bub’s principle approach arguing that if the mathematical formalism of quantum mechanics remains intact then there is no escape route from solving the measurement problem by constructive theories.”²⁴⁴

In “A Philosopher Looks at Quantum Information Theory,” Amit Hagar finds instrumentalism in QIT. “Suggestions to reformulate the axioms of QM in information-theoretic terms cannot be regarded as supplying a realistic foundation to QM ... [it is] nothing but instrumentalism in disguise. Of course there would be no science without scientists but this does not mean that the ultimate subject matter of science is the scientist

²⁴² Amit Hagar, and Meir Hemmo, “Explaining the Unobserved ---- Why Quantum Mechanics Ain’t Only About Information,” *Foundations of Physics* 36, no. 9 (September 2006), <http://web.ebscohost.com.libaccess.sjlibrary.org/ehost/pdf?vid=3&hid=21&sid=f13271bc-b3ae-4cc4-8422-32eb0e046bda%40sessionmgr2/> (accessed August 2, 2008)

²⁴³ The quantum measurement problem prompted the publication of the EPR paper and Schrodinger’s “cat paradox.” Briefly, the Schrodinger equation defines wave function evolution linearly as a superposition of multiple quantum states. *Until measurement, a particle-wave does not exist in a particular state but instead in a superposition of multiple states.* At measurement, the wave function collapses instantly. After that, its evolution is determined by the value of the measurement. *The act of measuring determines the value of the particle-wave/wave function.* Born statistics can be used to predict a probability distribution of possible values but not a single value. For more information, see Henry Krips, “Measurement in Quantum Theory,” *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, (Stanford: Metaphysics Research Lab, 2008), <http://plato.stanford.edu/archives/fall2008/entries/qt-measurement/> (accessed August 17, 2008)

²⁴⁴ According to Hagar and Hemmo, Bub’s holds that “Assuming the information-theoretic constraints are in fact satisfied in our world, no mechanical theory of quantum phenomena that includes an account of measurement interactions can be acceptable...the appropriate aim of physics at the fundamental level then becomes the representation and manipulation of information.” Hagar and Hemmo, “Explaining the Unobserved ---- Why Quantum Mechanics Ain’t Only About Information,” 2.

and his relation to the world, no matter how sensitive the latter is to his touch.”²⁴⁵

Quantum Information, Computing, and Cryptography

A field closely parallel to QIT, quantum computing (QC) reduces theoretically massively parallel computing efforts to quantum level operations on qubits.²⁴⁶ Although QC is not directly involved in the Platonic information theory introduced in this thesis, it is instructive. The field has a growing impact on related philosophical fields, particularly the Church-Turing principle.

This principle has been variously summarized. For example, according to the *The Stanford Encyclopedia of Philosophy*, Turing’s thesis is that “LCMs (logical computing machines: Turing’s expression for Turing machines) can do anything that could be described as ‘rule of thumb’ or ‘purely mechanical.’” And, Church’s is: “A function of positive integers is effectively calculable only if recursive.”²⁴⁷ Other writers similarly understand the joint thesis. Thus, the Church-Turing stipulates that “The class of ‘computable functions ... corresponds precisely to the class of functions which may be computed via what humans intuitively call an algorithm or procedure.’ ... A Turing

²⁴⁵ Amit Hagar, “A Philosopher Looks at Quantum Information Theory,” *Philosophy of Science* 70 (October 2003): 752-775.

²⁴⁶ A qubit is “a bit of quantum information. Unlike an ordinary bit. ... which can be expressed as either 0 or 1, a quantum bit is typically a combination of 0 and 1 [as a superposition].” Tom Siegfried, *The Bit and The Pendulum, From Quantum Computing to M Theory --- The New Physics of Information* (New York: John Wiley & Sons, Inc., 2000), 266. A traditional binary bit holds 0 or 1. Three bits can represent any single number from 0 to 7. With much more capacity, a group of three qubits can represent all the numbers 0 through 7 at the same time.

²⁴⁷ Jack B. Copeland, “The Church-Turing Thesis,” *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, (Stanford: Metaphysics Research Lab, 2008), <http://plato.stanford.edu/archives/fall2008/entries/church-turing/> (accessed August 17, 2008)

machine can compute anything that can be computed.”²⁴⁸

Many point to the physical notion of Church-Turing²⁴⁹ as model for a quantum computer.²⁵⁰ Others suggest that quantum computing algorithms *may exceed*²⁵¹ the theoretical *limit imposed on computing by Church-Turing* because quantum computing operates on qubits. Unlike classical Boolean (1 or 0, yes or no) operations, central to earlier computer theory, a quantum computation can determine the value of an “exclusive disjunction” in calculations (1-undecided-0, yes-not yet determined-no) that resolve upon

²⁴⁸ Siegfried, *The Bit and The Pendulum, From Quantum Computing to M Theory --- The New Physics of Information*, 250.

²⁴⁹ “Alonzo Church and Alan Turing independently proposed models of computation... Church invented the lambda calculus to study notions of computability while Turing used his Turing machines. Turing showed [both] were equivalent ... *Turing machines can do anything that can be described by a purely mechanical process.* ... [A]ny process that can be performed by an idealized mathematician can be simulated on a Turing machine.” Robert Sedgewick and Kevin Wayne, “Introduction to Programming in Java,” (2007), <http://www.cs.princeton.edu/introcs/75universality/> (accessed February 25, 2008)

²⁵⁰ David Deutsch, “Quantum theory, the Church-Turing principle and the universal quantum computer,” *Proceedings of The Royal Society of London*, A, 400 (1985), <http://cobnitz.codeen.org:3125/citeseer.ist.psu.edu/cache/papers/cs/13701/http:zSzzSzwww.qubit.orgzSzresourcezSzdeutsch85.pdf/deutsch85quantum.pdf> (accessed February 25, 2008)

²⁵¹ “The term ‘hypermachine’ denotes any data processing device ... capable of carrying out *tasks that cannot be performed by a Turing machine*. We present a possible *quantum algorithm for a classically non-computable decision problem, Hilbert’s tenth problem*; more specifically, we present a possible hypercomputation model *based on quantum computation* [my italics]. Our algorithm is inspired by the one proposed by Tien D. Kieu, but we have selected the infinite square well instead of the (one-dimensional) simple harmonic oscillator as the underlying physical system. Our model exploits the quantum adiabatic process and the characteristics of the representation of the dynamical Lie algebra $su(1,1)$ associated to the infinite square well.” Andres Sicard, Mario Véléz, and Juan. “A Possible Hypercomputational Quantum Algorithm,” in *Quantum Information and Computation III*, SPIE Defence and Security Symposium, (2005), <http://www.citebase.org/abstract?id=oai%3AarXiv.org%3Aquant-ph%2F0406137> (accessed February 25, 2008)

a superposition collapse.²⁵²

In 1982, Richard Feynman wrote that a Turing machine would have less computing ability than a device based on quantum mechanical principles.²⁵³ Feynman famously remarked “Nature isn’t classical ... if you want to make a simulation of nature, you’d better make it quantum mechanical ... [discussing the possibility of a quantum computer] It turns out ... that you can simulate this with a quantum system, with quantum computer elements ... *It’s not a Turing machine, but a machine of a different kind* [my italics].”²⁵⁴

In 1985, physicist David Deutsch explained how Church-Turing could be applied to quantum computing and that *nonlocal entanglement could be a computing mechanism*.²⁵⁵ Others following his suggestions developed successfully tested algorithms

²⁵² “Classical computational gates are Boolean logic gates that [manipulate] information stored in the bits.... *Quantum gates are unitary operators, i.e., they preserve the norm of the quantum state ...* Where there exists a universal gate ... the *NAND* gate which results from performing an *AND* gate and then a *NOT* gate, in quantum computing ... any multiple qubit logic gate may be composed from a quantum *CNOT* gate (which operates on a multiple qubit by flipping or preserving the target bit given the state of the control bit, an operation analogous to the classical *XOR*)... and single qubit gates. ... Unitary gates manipulate the information stored in the quantum register ... *ordinary (unitary) quantum evolution can be regarded as computation. In order to read the result of this computation... the quantum register must be measured. The measurement gate is a non-unitary gate that “collapses” the quantum superposition in the register onto one of its terms with the corresponding probability.* [my italics]” Amit Hagar, “Quantum Computing,” *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, (Stanford: Metaphysics Research Lab, 2008), <http://plato.stanford.edu/archives/fall2008/entries/qt-quantcomp/> (accessed August 17, 2008)

²⁵³ Brad Huntting, and David Mertz, “Introduction to Quantum Computing,” (2001), <http://www.ibm.com/developerworks/linux/library/l-quant.html> (accessed August 18, 2008)

²⁵⁴ Siegfried, *The Bit and The Pendulum, From Quantum Computing to M Theory --- The New Physics of Information*, 81-82.

²⁵⁵ “The conventional, non-physical view of [Turing’s machine] interprets it as the quasi-mathematical conjecture that all possible formalizations of the intuitive mathematical notion of ‘algorithm’ or ‘computation’ are equivalent to each other....it can also be regarded as asserting a new physical principle...the Church-Turing *principle* ... [that] ‘every finitely realizable physical system can be perfectly simulated by a universal model computing machine operating by finite means.’ ... [Q]uantum theory and

for quantum computing.²⁵⁶

Mark Burgin (Mathematics Department, UCLA) argues that “super-recursive algorithms” operating on infinite sets of data and for an unlimited time can exceed the theoretical limits imposed by the Church-Turing hypothesis. His “inductive Turing machine” operates without stopping.²⁵⁷ Arguing differently, Yu Shi (Cavendish Laboratory, University of Cambridge) finds that quantum entanglement prohibits the development of a quantum mechanical “universal Turing machine.”²⁵⁸

the ‘universal quantum computer’ are compatible with the [Church-Turing] principle... [a] universal quantum computer could... be built and *would have many remarkable properties not reproducible by any Turing machine* [my italics]. These do not include the computation of non-recursive functions, but they *do include ‘quantum parallelism’* [my italics], a method by which certain probabilistic tasks can be performed faster by a universal quantum computer than by any classical restriction of it. The intuitive explanation of these properties places an intolerable strain on all interpretations of quantum theory other than Everett’s. [Here, Deutsch refers to the “many worlds” interpretation of Edward Everett under which each wave function collapse spawns new quantum systems, one for each possible outcome.] David Deutsch, “Quantum Theory, The Church-Turing Principle and The Universal Quantum Computer,” *Proceedings of The Royal Society of London, Series A*, 400, (1985), <http://cobnitz.codeen.org:3125/citeseer.ist.psu.edu/cache/papers/cs/13701/http:zSzzSzwww.qubit.orgzSzresourceczSzdeutsch85.pdf/deutsch85quantum.pdf> (accessed July 20, 2008)

²⁵⁶ “While Deutsch’s problem ... has no interesting application, there now exist as several quantum algorithms for non-trivial problems, notably Shor’s factorization algorithm for factoring large composite integers in polynomial time (with direct application to ‘public key’ cryptography, a widely used classical cryptographic scheme) and Grover’s database search algorithm.” Bub, Jeffrey, “Quantum Entanglement and Information,” *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, (Stanford: Metaphysics Research Lab, 2009), <http://plato.stanford.edu/archives/spr2009/entries/qt-entangle/> (accessed July 20, 2008)

²⁵⁷ “[I]nductive Turing machines give results in a finite time, are more powerful and efficient than ordinary Turing machines and other recursive algorithms.... [However] that they do not inform when they get their results. However, this property makes them far better models for a majority of real-life systems and processes ... Super-recursive algorithms incorporate genuine creativity.... they bridge informal creativity and formal reasoning.” Mark Burgin, “The Rise and Fall of The Church-Turing Thesis,” *Computational Complexity* (2002), <http://arxiv.org/ftp/cs/papers/0207/0207055.pdf> (accessed July 20, 2008)

²⁵⁸ “In classical computation, any recursive function can be computed by a universal Turing machine, and the program is independent of the value of the variable. Generalizing this universality to quantum computation, one anticipates that there is a universal quantum Turing machine which can perform any desired unitary transformation on an arbitrary number of qubits, by including a program as another part of the input state; or the program effecting a unitary transformation is independent of the state of qubits to be computed... [H]owever, due to entanglement, neither of these two situations exists... one may argue that it

Quantum cryptography emerged as an adjunct to quantum computing using entanglement to assure the security of transmitted information. Commercially, entangled photon systems have been used to safely send information about large bank transfers. The keys, used to decode transaction messages, are available at distantly separated locations as entangled pairs of photons. “Quantum key distribution does not invoke the transport of the key, since it is created at the sender and receiver site immediately ... eavesdropping is easily detected due to the fragile nature of the qubits invoked for the quantum key distribution.”²⁵⁹ In addition to demonstrating quantum teleportation over a relatively long distance (144 km), Anton Zeilinger (Physics Department, University of Vienna) was the first to show the practicality of quantum entanglement-based cryptography. The Institute of Physics recognized the significance of this work by awarding Zeilinger the first Issac Newton medal in 2007, noting the importance of “the rapidly evolving field of quantum information” in many fields including cryptography.²⁶⁰

As this aside indicates, quantum nonlocality has fostered potentially practical new fields such as QIT-related quantum computing, teleportation, and cryptography. It is certainly worthy of an open-minded approach to philosophical explanation.

is classical physics and classical computation, not quantum mechanics and quantum computation, that is compatible with the Church-Turing thesis or principle.” Yu Chi, “Is There a Universal Quantum Computer?” (February 25, 2002), http://arxiv.org/PS_cache/quant-ph/pdf/9805/9805083v4.pdf (accessed July 21, 2008)

²⁵⁹ See “Quantum Cryptography with Entangled Photons” *Quantum Cryptography* (2008), <http://www.quantenkryptographie.at/> (accessed July 21, 2008)

²⁶⁰ Hamish Johnston “Anton Zeilinger Scoops First Issac Newton Medal,” *physicsworld.com*, <http://physicsworld.com/cws/article/news/31379> (accessed August 2, 2008)

Is QIT About Information, Physical Reality, or Both?

As this survey sample of QIT writing indicates, its proponents claim equal status with classical quantum theory. The sampled opponents point out that QIT has not addressed the measurement problem and may be instrumentalist.²⁶¹

The last criticism is perhaps the most telling, is QIT about information concerning quantum phenomena, quantum phenomena, or both? QIT takes QM formulations (for example, Schrodinger equation) as given, deriving two of its three “constraints”²⁶² from QM. In this respect, QIT may be as much about quantum phenomena as QM.

The questions about the truth or realistic accuracy of QM formulations (for example “how do wave function evolution and measurement-associated collapse correspond to physical reality?”) can be asked about QIT. Both are probabilistic and necessarily include nonlocality. Both fail to answer Einstein and Schrodinger’s questions about a relationship to local reality. QIT’s focus on information does not preclude assuming that there is something physical associated with or generating the information.

²⁶¹ The instrumentalist versus realist positions on science was recently summarized. “The *instrumentalists* ... think... that theories are merely conceptual tools for classifying, systematizing and predicting observational statements, so that the genuine content of science is not to be found [in]... theories. *Scientific realists*, by contrast, regard theories as attempts to describe reality... beyond the realm of observable things and regularities... theories can be regarded as statements having a truth value. Excluding naive realists, most scientists [hold that] scientific theories are hypothetical and always corrigible in principle. They may happen to be true, but we cannot know this for certain in any particular case. But even when theories are false, they can be cognitively valuable if they are closer to the truth than their rivals. Theories should be testable by observational evidence, and success in empirical tests gives inductive confirmation or non-inductive corroboration to the theory.” Ilkka Niiniluoto, “Scientific Progress,” *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, (Stanford: Metaphysics Research Lab, 2008), <http://plato.stanford.edu/archives/spr2009/entries/scientific-progress/> (accessed July 20, 2008)

²⁶² No superluminal information transfer and “impossibility of perfectly broadcasting information contained in an unknown physical state.” Clifton, Bub, and Halvorson, “Characterizing Quantum Theory in Terms of Information-theoretic Constraints,” 1587.

QIT may be as much about physical phenomena as QM is. This thesis takes an information-centric approach suggested by QIT (without the three constraints) but retains the “hidden variable—guiding equation” requirement of EPR, Bohm, and deBroglie but rejected by QIT.

Interpreting Quantum Hidden Variables as Information

Hidden variables have been variously defined as “deterministic, stochastic, local, and nonlocal.” Not quantum states, they serve as a causal mechanism for the nonlocal but associated events observed in measurements of quantum entangled systems.²⁶³

This thesis proposes a new Platonic interpretation of hidden variables. Like mathematical Platonic entities, they “exist” outside space-time. Unlike most modern Platonic formulations, this one takes an approach suggested by a contemporary field of physical theory, quantum information theory (QIT).

Adopting an information-centric approach, this thesis suggests that QM measurements as information may be expressed in qubits. Going beyond a QIT restriction, this thesis allows hidden variables—guiding equation and suggests that if detected, they may be quantified in qubits.

²⁶³ “Can quantum probabilities and correlations be obtained as averages over variables at some deeper level than those specifying the quantum state of a system? If such quantities exist they are called hidden variables. Many different types of hidden variables have been proposed: deterministic, stochastic, local, nonlocal, etc. A number of proofs exist to the effect that positing certain types of hidden variables would force probabilistic results at the quantum level that contradict the predictions of quantum mechanics.” *The Cambridge Dictionary of Philosophy*, ed. Robert Audi (Cambridge: Cambridge University Press, 1999), 703.

Part Four: Information Platonism

Overview

In the earlier and modern expressions of Platonism, forms are uncreated and only discovered or perceived incompletely by minds. Accepting these restrictions (external to space-time, uncreated, instantiation-only-association with phenomenal objects, and incapable of complete apprehension by minds), how can we reasonably interpret an observable physical phenomenon Platonically? Benjamin Callard recently argued that abstract Platonic entities can cause affect physical minds “without the benefit of contiguity relation.”²⁶⁴ Although he did not provide a model for the mechanism of interaction, he strongly argued that it is not philosophical impossible. A medium of connectivity may have been implied in quantum information studies in physics for several years. This part of the thesis suggests that a Platonic connection to the physical world exists as quantum-level information.

Objects of Modern Mathematical Realism-Platonism and Information Platonism

Mathematical Realists and Platonists²⁶⁵ vary in identifying things that exist Platonically. James Robert Brown²⁶⁶ argues for a Platonism that includes all mathematical objects and relationships including organizing principles of the universe. Michael Tooley includes causality within the Platonic realm. Although she no longer writes as a Platonist, Susan Hale formerly argued interestingly, following Werner

²⁶⁴ See “Benjamin Callard” in the section “Mathematical Realism,” in this thesis.

²⁶⁵ Grouped together in this thesis.

²⁶⁶ See “James Robert Brown” in the section “Mathematical Realism,” in this thesis.

Heisenberg's lead, that quantum level objects could be described not as physical entities but instead as "complicated states, perhaps as mathematically-described states of fields."²⁶⁷ Jerrold Katz argues that we do not casually connect with abstract objects sensually but instead through the mind's *a priori* ability to conceive abstract mathematical objects and truth. He includes "number theoretic facts ... numbers, propositions, and expressions (in the type sense) ... [and] abstract relation between abstract objects" among the Platonic.²⁶⁸ Richard Tieszen argues for a "consciousness of abstract objects" supported by the consensus of many minds. He recognizes our indebtedness to Gödel, holding that the Incompleteness Theorems may demonstrate the existence of abstract mathematical objects. Identifying items that he would include as Platonic, Rick lists "geometric objects, natural numbers, real numbers, complex or imaginary numbers, functions, groups, sets, or categories, and truths about these objects." He notes that other Platonists may also include "intentional objects" such as "meaning, propositions, concepts, or essences."²⁶⁹

Although opinions about the content of the Platonic realm may differ among theorists, many agree that these objects or relationships are unchanging and outside spacetime. Sometimes they point to the criteria of Graeco-Roman precursors of modern mathematical realism, Pythagoras, Parmenides, Plato, Plotinus, and others who argued for immutably unchanging, uncreated, eternal, and indivisible forms. Today, many hold

²⁶⁷ See "Susan Hale" in the section "Mathematical Realism," in this thesis.

²⁶⁸ See "Jerrold Katz" in the section "Mathematical Realism," in this thesis.

²⁶⁹ Tieszen, "Mathematical Realism and Transcendental Phenomenal Realism," 3.

that no physical event is directly related to the instantiation of Platonic entities.

However, a few theorists including Roger Penrose and Max Tegmark argue for physical correlations in the observable universe. This thesis follows their example, arguing that a physical correlation can be postulated. Unlike Penrose's focus on Platonic instantiation brain structures, my position is closer to (but different than) Tegmark's that "mathematical existence and physical existence are equivalent ... asserting that the mathematical structures in Plato's realm of ideas ... exist 'out there' in a physical sense." In Tegmark's model, all physical objects (as well as mathematical abstractions and intensions) are equated with Platonically real mathematical structures. More particularly, this thesis identifies the information expressed in a quantum wave function collapse as Platonic.

While this thesis focuses on one type of Platonic object (information), it also accepts mathematical objects and interrelations, intentional objects, and causal agents proposed by Brown, Tooley, younger Hale, Callard, Katz, Tieszen, and Tegmark for the Platonic realm.

Information Platonism Instantiations

More physically than Penrose's scheme, this thesis proposes a mind-independent (but not mind-unaware) model of Platonic instantiation. More specifically than Tegmark, this thesis argues that a currently widely accepted, mathematically-described, predictably and unpredictably occurring, unobservable quantum phenomena, *wave function collapse* or reduction, is a *physical event that correlates to Platonic instantiation*. More than merely correlated, *they are equivalent*, borrowing an expressing from Tegmark. The

instantiation “puts” quantum information into a local physical environment that did not exist (in the environment) before the instantiation.²⁷⁰ The view that the *measured outcome of wave function collapse is new information is not original*.²⁷¹ Interpreting the process as Platonic is, however.

Although the narrow goal of this thesis is to interpret quantum nonlocality, arguing that the wave function collapse or decoherent reduction at the end of entanglement (upon measurement or observation) is associated with Platonic instantiation, *to avoid inconsistency, I also postulate that every wave function instantiation is associated with a Platonic instantiation.*

The Information Platonism of this thesis postulates that *at its instantiation, every type of Platonic object* (mathematical objects and relations, “intentions,” causality factors, wave function collapse created quantum values, and others) *is expressed as information.* Some are realized in the mind, others may be mind-independent expressions in physical events.²⁷²

Similarly to other proponents of Platonism, I assume that each instantiation is

²⁷⁰ This interpretation of Platonic entities as “information” may meet the criteria set by Mark Balaguer. He argues that *belief in real objects is justified if one could explain how they might exist*. See the summary description of Balaguer’s position presented in *Platonism and Anti-Platonism in Mathematics* (Oxford: Oxford University Press, 1998) reviewed in “Mark Balaguer, Platonism and Anti-Platonism,” *British Journal of the Philosophy of Science*, 50 (1999): 775-780.

²⁷¹ “Upon measurement, the wave function collapses to reflect the information gained,” Alan Weinstein, “Wave function collapse, quantum reality, EPR, Bell’s Theorem, and all that.” *CiteSeerx* (2007), [http://citeseer.ist.psu.edu/weinstein96wave function.html](http://citeseer.ist.psu.edu/weinstein96wave%20function.html) (accessed May 12, 2008)

²⁷² Although he is not a traditional Platonist, Karakostas (and some others) postulates mind-independent quantum-level “wholes” that cannot be observed. On the other hand, several traditional physicists including Bohr argued that the mind must be involved in measurements for quantum events to occur.

incomplete in terms of the total amount of potentially expressible information. For example, mathematically, the ideal form of a circle exists as Platonic information but only inexactly as a constructed circle. Similarly, measurements of a system correspond to particular object instantiations of Platonic information. For example, the Platonic information of the total evolution of a wave function (ψ) is the instantiations in ST plus possible-but-uninstantiated information. Here, the quantum state of a particular wave function measured during a time period is a partial instantiation of the total information. In the following section, an Information Platonism instantiation is represented as PI.²⁷³

Borrowing Susskind's entropic information model, we may be able to substitute "all Platonic information (instantiated and uninstantiated) of object a" (PI_{all}) for his "maximum entropy" of object "a" to arrive at a total amount of instantiated Platonic information.

If the relative "size" or "content" of Platonic sets of information could be compared,²⁷⁴ the result would be: $\sum PI_{all} > PI_{a-n_{all}} > PI_{a_{all}} > PI_{a_{inst}}$

where, $\sum PI_{all}$ is the set of all Platonic information (instantiated and uninstantiated) for all possible Platonic objects (mathematical and others) in the physical universe (PU), $PI_{a-n_{all}}$ is the set of all possible Platonic information (instantiated and uninstantiated) for all possible states of all objects in PU, $PI_{a_{all}}$ is the set of all possible Platonic information

²⁷³ ΨR symbolizes "wave function collapse" in Figure 1. It is expressed as Platonic instantiation in this thesis. In other words, $\Psi R = PI$.

²⁷⁴ In some ways, this would similar to comparing Cantor's transfinite sets.

(instantiated plus uninstantiated) for a specific object “a” in PU, and $PI_{a_{inst}}$ is the set of all Platonic information instantiated in the PU for the object “a.” Individual PI_{inst} are expressed only at the quantum-level in the PU. The stochastic aggregate of a large number of instantiations constitute observed phenomena occurring in the observable portion of the physical universe (OU).²⁷⁵

Wavefunction Collapse as Platonic Instantiation

Bohmian mechanics does away with the wave function collapse or reduction, interpreting the event as a “conditional wave function of a subsystem ... configuration evolving according to a ‘guiding equation.’”²⁷⁶ Differently, standard quantum theory assumes almost constant wave function collapses (also known as “state vector collapse” or “state reduction”), as systems evolve and interact with other systems. A few theoreticians postulate additional unpredictable, “spontaneous” wave function collapses such as the “Ghirardi, Rimini, and Weber (GRW) involving a nonlinear, stochastic evolution of the wave function.”²⁷⁷

Unlike Bohmian mechanics, this thesis accepts both interactive-prompted and spontaneous wave function collapse. I equate wave function collapse with the instantiation of Platonic information and identify the instantiated information with Bohm-

²⁷⁵ Much of the PU is composed of only indirectly observable but widely accepted “dark matter” and “dark energy.” See Lee Smolin, *Three Roads to Quantum Gravity*, 14-16, 150, 191-192 for discussions focusing on dark matter and energy.

²⁷⁶ Maudlin, *Quantum Nonlocality and Relativity*, 117.

²⁷⁷ Roderich Tumulka, “On Spontaneous Wave Function Collapse and Quantum Field Theory” (2005), <http://arxiv.org/abs/quant-ph/0508230> (accessed June 12, 2008)

deBroglie's "hidden variables" or "guiding equation." In the following figure, wave function collapses (interaction-prompted and spontaneous) are represented (ψ_R).

In this thesis, a quantum system (single particle, entangled pair, and so on) wave function collapse is immediately associated with a Platonic instantiation of quantum information at the spacetime point of measurement/interaction.²⁷⁸ These relationships are represented below.

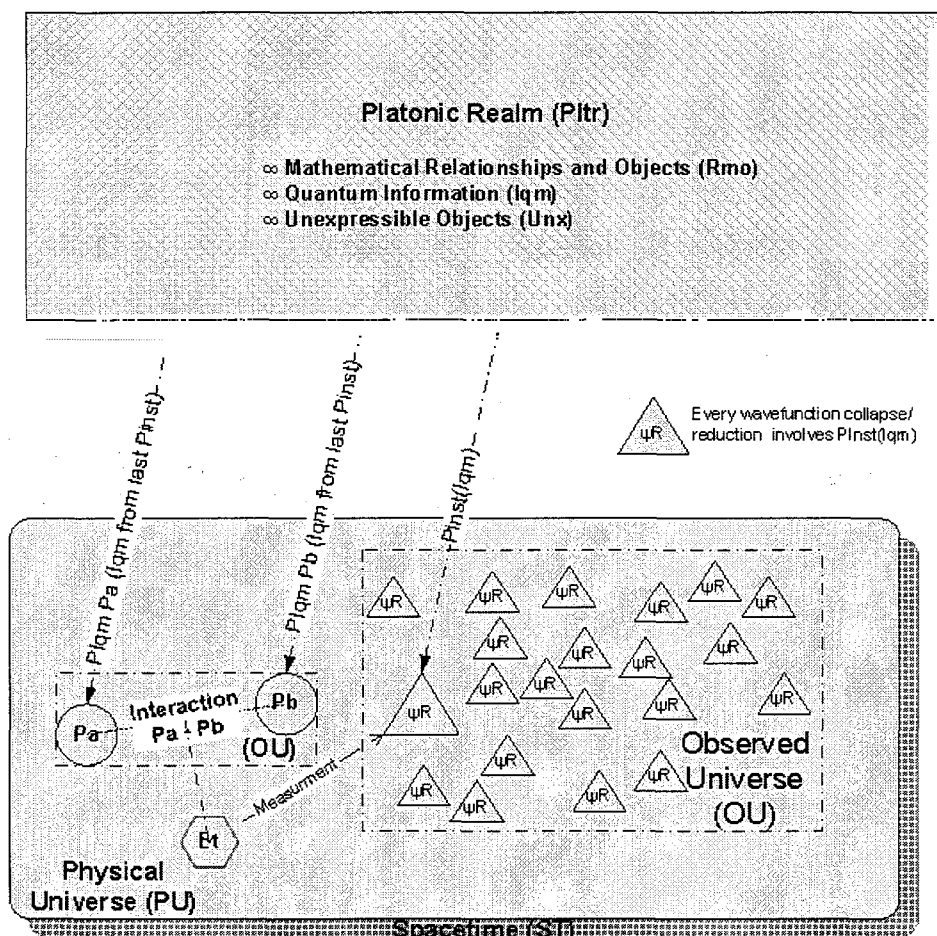


Figure 1. Platonic Information Instantiation

²⁷⁸ Many theoreticians have discussed the association of wave function collapse with information transfer. See Alan Weinstein, "Wave function collapse, quantum reality, EPR, Bell's Theorem, and all that." *ibid*.

In Figure 1, the Platonic realm (Pltr) is outside spacetime (ST), separate from the physical universe (PU)²⁷⁹ which is within ST.²⁸⁰ Within PU, the observed universe (OU) consists of multiple wave function instantiations (ψ R) which occur at measurements /interactions at definite locations and times. Within ST, unpredictable quantum fluctuations occur as a corollary of Uncertainty Relations. However, because these quantum-level appearances and disappearances (inside and outside OU) do not involve wave function collapse,²⁸¹ they are not included in this model. Their total persisting information, like their total mass, is zero.

The total Platonic information, existing in the Platonic realm, associated with objects Pa and Pb in the physical universe (PU) includes both instantiated and uninstantiated existentially-contingent information.²⁸² Particles Pa and Pb may possess the PIqm from the last Platonic instantiation.²⁸³ The observable portion of this information exists at a wave function collapse.

²⁷⁹ This Platonic model postulates a single physical universe. An Everettian multiverse model would involve a separate set of possible Pltr-to-PU relationships for each universe. Differences between the universes (for example, the fine structure constant) could result in differences between the relationship sets.

²⁸⁰ Spacetime (ST) includes more than the physical universe.

²⁸¹ See H.E. Puthoff, "Quantum Fluctuations: a New Rosetta Stone of Physics," <http://ldolphin.org/zpe.html> (accessed June 10, 2008)

²⁸² Plato considered both uninstantiated and partially instantiated "forms." Differently, Aristotle only defined forms as instantiated in material objects. This discussion follows Plato's lead.

²⁸³ Whenever a new measurement/interaction occurs, the PIqm of an object will change.

Instantiation Environments

Process discussions about Platonic instantiations are extremely rare. One is Penrose's description of neuronal microtubules as the site of instantiations. Typically, a mathematical or physical Platonist will allude to rather than specify the affect of Platonic forms on the mind. Because this thesis extends the concept of Platonic entity to information about physical systems with or without the measurement presence of sentient observers, a discussion of instantiation-without-minds is appropriate.

Within Minds

Many Platonists, including perhaps the majority of mathematical realists, identify the human mind as the sole location of instantiation. For them, it is a mental condition or event. This thesis differs. At the human level, I agree with Rick Tieszen that we do have a "consciousness of the abstract." If we accept Platonism, we may also observe evidence of Platonic instantiation in the physical universe outside ourselves. Although our human recognition of the hexagonal regularity of some honeycombs may involve "consciousness of abstract" mathematical forms, the observed physical forms were constructed by honey bees. Do we extend this "consciousness of the abstract" to bees and even simpler organisms who construct geometrically regular figures? Whatever "instinct" is, does its expression involve the attempt to construct, as perfectly as possible, a replica of Platonic forms? Is this genetically encoded Platonic consciousness? If so, the "instantiation" in the awareness of bees is prepared by a physical mechanism.

Beyond Minds

Suggesting an empirical aspect, this thesis argues that mathematical regularities that may be correlated with Platonic instantiation occur outside the mind in addition to occurring within. Widely accepted laws of physics are frequently symbolically represented in Platonic-like symmetries. Physical observations have verified many of these regularities. Although we may perceive them, these regularities exist even if we do not. At the quantum-level, this thesis extends Platonic instantiation to “hidden variables-guiding equations” which if they exist are, by definition, unobserved and therefore, also outside minds.

Platonic Quantum Information

Under this scheme, Platonic quantum-level information for a physical object consists of all existentially-contingent information, fundamental properties that are necessary for all states of an object or field (such as mass, quantum states, etc.) to physically exist in spacetime (ST).

Part Five: Conclusion

Overview

Although many theoretical and mathematical physicists are disinterested in questions about the relative “realism”²⁸⁴ or “antirealism”²⁸⁵ of aspects of quantum theory, the debate continues in philosophical circles. Building on these discussions, this thesis proposes a Platonic interpretation of the “hidden variables” explanation of quantum nonlocality.

This conclusion restates the proposition of this thesis that:

- The content of the “Platonic realm” may be interpreted as information. Some of this Platonic information is instantiated (recognized) in minds as mathematical objects and relations among them. Some of this content is also instantiated outside of minds²⁸⁶ as quantum states in wave function collapses.
- The measurement of any quantum effects including nonlocality (entanglement) are examples of these wave function-Platonic instantiations.
- The explanatory role of “hidden variables” or “guiding equation” for

²⁸⁴ Jens Heber, *The Standard Conception As Genuine Quantum Realism* (Odense: University of Southern Denmark, 2005).

²⁸⁵ B. Van Fraassen, “The charybdis of realism: Epistemological implications of Bell’s inequality” in *Philosophical Consequences of Quantum Mechanics*, ed. J. Cushing and E. McMullin (Notre Dame: University of Notre Dame Press, 1989), 97-113.

²⁸⁶ This thesis does not address the issue raised by Bohr and others in the 1920s – 30s, that minds conduct or control quantum-level measurements. I realize that there are no quantum measurements or in the view of this thesis, Platonic instantiations that are completely “outside of minds.” However, to limit the scope of this thesis, I accept Einstein’s view that the universe exists of itself, external to minds.

nonlocal effects may be replaced by wavefunction Platonic instantiations of quantum information at the measurement site.

This position is summarized below.

Assumptions

This thesis makes basic assumptions about aspects of quantum mechanics (QM) and Platonism. It assumes the following:

- 1) QM is a demonstrated but incomplete representation of the quantum-level physical universe.

Broadly, this is the position taken by Einstein-Podolsky-Rosen (EPR), Schrodinger, deBroglie, Bohm, and a few other theoretical physicists in the early 20th century.²⁸⁷ However, the great majority of physicists accepted the views (e.g., Copenhagen interpretation) that quantum theory adequately explains observed phenomena.

The incompleteness involves:

- Inadequate physical explanation of a wave function collapse.

Bohm rejected any wave function collapse. According to Bohmian mechanics, a quantum system evolves according to the Schrodinger equation with the addition of a “guiding equation” or “hidden variables.”

- Incomplete explanation of quantum nonlocality-entanglement.

Bohm, deBroglie, and a few other physicists argued that QM nonlocality implies incompleteness.

- No generally accepted merger of QM and Special Relativity and General Relativity (SRGR).

Many contemporary theoretical physicists (Smolin, Randall, and others) propose unification models arguing that there is no currently generally accepted way to combine QM as it is and GR. However, this topic is beyond the narrow scope of this thesis

- 2) Quantum nonlocality (entanglement) is a demonstrated physical phenomenon.

Beginning with Alain Aspect's work in 1982, many physicists have experimentally demonstrated quantum nonlocality. In the past 25 years, entanglement has become a practical tool to develop "unbreakable" protocols for transferring information. Recent experiments have entangled three particles in macroscopic solids.²⁸⁸

- 3) The quantum-level physical phenomena explained by QM may be interpreted as information.

Quantum information theory (QIT) proposes an information-theoretic approach to quantum-level physical phenomena. Although its tenets do not presently explain all quantum phenomena (for example, the measurement

²⁸⁷ Michael Bitbol, *Schrodinger's Philosophy of Quantum Mechanics* (Boston: Kluwer Academic Publishers, 1998), 115.

²⁸⁸ Jon Cartwright, "Multi-particle entanglement in solid is a first," *Physicsworld* (June 5, 2008), <http://physicsworld.com/cws/article/news/34499> (September 1, 2008)

problem is unexplained), it is a useful perspective. A similar information-theoretic approach is taken in this thesis.

- 4) A Platonic realm including mathematical and other objects exists outside spacetime (ST) that affects spacetime, the physical universe, and objects (observable and unobservable) in the physical universe.²⁸⁹

This thesis postulates a “Platonic realm” or unbound set of Platonic things as “indispensable”²⁹⁰ to physical explanation and theory. Like other Platonic models, mine assumes that this set is external to ST. Unlike many other Platonic theories, this one assumes that Platonic objects affect the observable universe whether or not minds think about them.

Argument

Accepting the assumptions listed in the previous section, this thesis makes the following argument for a Platonic interpretation of the “hidden variables” explanation for quantum nonlocality:

- 1) Platonism includes both mathematically-related and physically-related content.

Accepting the “full-blooded Platonism”²⁹¹ of some mathematical

²⁸⁹ Many theorists including Tieszen group mathematical realism and Platonism together.

²⁹⁰ Colyvan, “Indispensability Arguments in the Philosophy of Mathematics,” *ibid.*

²⁹¹ Mark Balaguer, “Can We Know That Platonism Is True?” in book review: *Realistic Rationalism*,” *The Philosophical Forum*, XXXIV, no. 3, 4 (Fall-Winter, 2003): 463.

realists, the Platonic realm²⁹² incorporates mathematical relationships including the symmetries noted by Penrose.²⁹³ As a “full-blooded” model, it also includes other relationships, not currently expressible by minds. The realm includes all possible quantum level information.²⁹⁴ This model also looks to the work of MIT physicist Max Tegmark who argues that the external existence of the universe (“External Reality Hypothesis” or “ERH”) outside of minds implies mathematical realism (“Mathematical Universe Hypothesis” or “MUH”). He further argues that our “external physical reality” is actually a “mathematical structure” (“Computable Universe Hypothesis” or CUH”) and “defined by computable functions.”²⁹⁵

2) The mathematical-physical content Platonic realm is information.

Combining the information-theoretic approach of QIT with this model of “Information Platonism” enables us to interpret quantum-level information Platonically.²⁹⁶ Apparently, this view contrasts with traditional Platonism.

In classical Platonism, perceived “information” is distinguished from “knowledge.” We obtain information through limited human perception.

Differently, we “know” Platonic entities through mental “recognition” of ST-

²⁹² In Figure 1, the Platonic realm is symbolized as “Ptr.”

²⁹³ See the section “Roger Penrose,” in this thesis.

²⁹⁴ In the figure, quantum information is symbolized as “Iqm.”

²⁹⁵ See the section “Max Tegmark,” in this thesis.

²⁹⁶ See “Information Platonism,” in this thesis, for a brief description of the suggested field.

external forms. Because we are reborn, we can correctly judge things and relationships by comparing them with the eternal Forms that we recognize or recollect from before birth. Plato argued for a hierarchy of knowledge. From conjecture, it advances to knowledge of physical objects, to understanding or deductive knowledge about mathematics (e.g., Pythagorean principle),²⁹⁷ and finally to rational intuition of the Forms themselves. For Plato, the philosopher's task is to seek higher levels of knowledge (through a combination of mental exercise and recollection) and teach others to do the same.²⁹⁸

The physical information-theoretic approach of this thesis does not have to contrast strikingly with classical Platonism. One could approximately correlate Plato's "hierarchy of knowledge" with the progression from physical measurements to an understanding of mathematical laws of physical nature to a rational Tegmark-like MUH postulation of Platonic entities.

And, "Platonic Information" narrowly refers to outside-ST, abstract entities that are only partially and never completely "perceived." Quantum superposition limits the completeness of their instrumental measurement (e.g., Heisenberg's Uncertainly Relations).

²⁹⁷ Richard D. Mohr, "Number Theory in Plato's Republic VII and Philebus" *Isis*, 72, no. 4 (1981), [//links.jstor.org/sici?sici=0021-1753%28198112%2972%3A4%3C620%3ATNTIPR%3E2.0.CO%3B2-V](https://links.jstor.org/sici?sici=0021-1753%28198112%2972%3A4%3C620%3ATNTIPR%3E2.0.CO%3B2-V) (accessed June 10, 2008)

²⁹⁸ *PLATO, COMPLETE WORKS*, eds. John M. Cooper and D.S. Hutchinson (Indianapolis: Hackett Publishing Company, 1997).

3) Platonic instantiations occur within and without minds.

Platonic information content is instantiated in both mental activities and mind-independent physical events. For example, regular geometric structures emerge as crystals “grow.” Minds observe crystals, possibly recognizing their Platonic shapes. But these regular atom-to-atom arrangements exist whether or not minds perceive them.

4) Mind-independent physical Platonic instantiations occur within ST at locations in the physical universe PU.

Physical objects (e.g., particles) exist at locations within ST. Each measurement of- or interaction with a QM-describable particle is associated with wave function collapse.²⁹⁹

These quantum-level events (wave function collapses) are Platonic information instantiations.³⁰⁰ Although quantum wave function or probability wave collapse, the corollary of measurement, has been widely accepted in QM theory since the 1930s, it is not a physically-observable phenomena.³⁰¹ It is a mathematical construct. Some theories such as Bohmian mechanics and Everett’s multiverse theories drop the idea as conceptually unnecessary.

This thesis accepts the wave function collapse as an event but

²⁹⁹ This statement is based on mainstream (non-Bohmian) QM theory.

³⁰⁰ See “Wave function Collapse as Platonic Instantiation,” in this thesis.

³⁰¹ “After more than seven decades, no one understands how or even whether the collapse of a probability wave really happens.” Greene, 119.

reinterprets the cause for the availability of quantum state information after the collapse. Unlike standard QM theory (e.g., Copenhagen) that makes until-the-collapse-only-potential measurements of location or momentum “real” at the collapse, this thesis argues that these same measurements are until-the-collapse-only-potential observations of Platonic information. Similarly to Tegmark, this thesis argues that these physically-measured factors (e.g., momentum) are actually abstract, Platonic entities.

Furthermore, this thesis argues that wave function collapse is a mind-independent mechanism of Platonic instantiation.

- 5) The measurement (detection) of a member of quantum nonlocal entanglement is associated with the wave function collapse of all members of the entangled system.³⁰²

This is a standard QM interpretation of what happens when a member of an entangled system is measured.

- 6) Platonic information is expressed at the wave function collapse of an entangled system.

See 4), above.

- 7) The “hidden variables-guiding equation” of deBroglie-Bohm is potential, yet-to-expressed-in-wave function collapse Platonic information about the quantum states of the members of an entangled system.

Returning to the deBroglie-Bohmian model, this thesis substitutes Platonic information (instantiated at wave function collapse) for their “hidden variables” or “guiding equations” to explain quantum nonlocality.

³⁰² Giancarlo Ghirardi, "Collapse Theories", *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, (Stanford: Metaphysics Research Lab, 2008), <http://plato.stanford.edu/archives/fall2008/entries/qm-collapse/> (accessed September 25, 2008)

Bibliography

- Aczel, Amir D. *Entanglement*. New York: Penguin Books, Ltd., 2003.
- Alfred North Whitehead. *Process and Reality: An Essay on Cosmology*. New York: Free Press, 1929.
- Aspect, Alain, Jean Dalibard, and Gnaud Roger. "Experimental Test of Bell's Inequalities Using Time Varying Analyzers." *Physical Review Letters* 49 (1982):1804–1807
- Atkinson, D. "Losing Energy in Classical, Relativistic, and Quantum Mechanics," *Studies in History and Philosophy of Modern Physics*, 38, no 1 (March 2007): 12.
- Audi, Robert, General Editor, *The Cambridge Dictionary of Philosophy*, Second Edition, Cambridge: Cambridge University Press, 1999.
- Balaguer, Mark. "Can We Know That Platonism Is True?" *Realistic Rationalism, The Philosophical Forum*, XXXIV, no. 3, 4 (Fall-Winter, 2003): 516-518.
- Barbour, Julian, *The End of Time*. Oxford: Oxford University Press, 1999.
- Barrow, John D. *New Theories of Everything*. Oxford: Oxford University Press, 2007.
- Bell, John. *Speakable and Unspeakable in Quantum Mechanics*. Cambridge: Cambridge University Press, 1987.
- . "Free Variables and Local Causality." *Speakable and Unspeakable in Quantum Mechanics*. Cambridge: Cambridge University Press, 1987.
- . "On the Problem of Hidden Variables in Quantum Mechanics," *Reviews of Modern Physics*, 38, no. 3 (July 1966).
- . "On Einstein Podolsky Rosen Paradox," *Physics*, 1, no. 3 (1964)
- Berkovitz, Joseph, and Meir Hemmo. "Modal Interpretations of Quantum Mechanics and Relativity: A Reconsideration," *Foundations of Physics* (March 2005).
<http://philsci-archive.pitt.edu/archive/00001993/02/Berkovitz@Hemmo.FoundPhys.pdf>
(accessed September 12, 2008)
- Beyer, Christian, "Edmund Husserl," *The Stanford Encyclopedia of Philosophy*. Edited by Edward N. Zalta, Stanford: Metaphysics Research Lab (2008),
<http://Plato.stanford.edu/entries/husserl/#PheEpo> (accessed June 14, 2008)
- Bitbol, Michael, *Schrodinger's Philosophy of Quantum Mechanics*. Kluwer Academic Publishers: Boston, 1998.

- , Bitbol, “Physical Relations or Functional Relations? A Non-metaphysical Construal of Rovelli’s Relational Quantum Mechanics,” *Philosophy of Science Archives* (Sept. 11, 2007), <http://philsci-archive.pitt.edu/archive/00003506/01/RelationsRovelli.pdf> (accessed August 7, 2008)
- Brown, James Robert. *Smoke and Mirrors: How Science Reflects Reality*. New York: Routledge, 1994.
- Bub, Jeffrey, “Quantum Mechanics is About Quantum Information.” *Foundations of Physics* 35, no. 4: 541-560.
<http://web.ebscohost.com.libaccess.sjlibrary.org/ehost/pdf?vid=17&hid=114&sid=e01d83ab-85bb-4cd8-a667-ca9dd9806b09%40sessionmgr3> (accessed August 1, 2008)
- , “Quantum Entanglement and Information,” *The Stanford Encyclopedia of Philosophy*. Edited by Edward N. Zalta, Stanford: Metaphysics Research Lab (2006), <http://Plato.stanford.edu/entries/qt-entangle/> (accessed July 20, 2008)
- Burgin, Mark. “The Rise and Fall of The Church-Turing Thesis.” *Computational Complexity*. (2002), <http://arxiv.org/ftp/cs/papers/0207/0207055.pdf> (accessed July 20, 2008)
- Callard, Benjamin. “The Conceivability of Platonism.” *Philosophia Mathematica* 15,
<http://philmat.oxfordjournals.org.libaccess.sjlibrary.org/cgi/content/full/15/3/347?maxtoshow=&HITS=10&hits=10&RESULTFORMAT=&fulltext=Plato&searchid=1&FIRSTINDEX=0&volume=15&issue=3&resourcetype=HWCIT> (accessed August 5, 2008)
- Cartwright, Jon, “Multi-particle Entanglement in Solid is a First,” *Physicsworld* (June 5, 2008), <http://physicsworld.com/cws/article/news/34499> (September 1, 2008)
- Chi, Yu. “Is There a Universal Quantum Computer ?” (February 25, 2002), http://arxiv.org/PS_cache/quant-ph/pdf/9805/9805083v4.pdf (accessed July 21, 2008)
- Clifton, Rob, Jeffrey Bub, and Hans Halvorson, “Characterizing Quantum Theory in Terms of Information-theoretic Constraints.” *Foundations of Physics* 33, no. 11 (April 2003),
<http://web.ebscohost.com.libaccess.sjlibrary.org/ehost/pdf?vid=3&hid=21&sid=f13271bc-b3ae-4cc4-8422-32eb0e046bda%40sessionmgr2> (accessed August 1, 2008)
- Colyvan, Mark, “Indispensability Arguments in the Philosophy of Mathematics,” *The Stanford Encyclopedia of Philosophy*. Edited by Edward N. Zalta, Stanford: Metaphysics Research Lab (2008), <http://Plato.stanford.edu/entries/mathphil-indis/> (accessed September 27, 2008)

- Cooper, John M. and D.S. Hutchinson, eds. *PLATO, COMPLETE WORKS*. Indianapolis: Hackett Publishing Company (1997).
- Copeland, B. Jack. "The Church-Turing Thesis," *The Stanford Encyclopedia of Philosophy*. Edited by Edward N. Zalta, Stanford: Metaphysics Research Lab (2002), <http://Plato.stanford.edu/entries/church-turing/> (accessed August 17, 2008)
- Cramer, John G. "Interpreting Quantum Mechanics," *Science, Letters*, 221, no. 4605 (July 1983): 6.
- Daintith, John, Elizabeth Martin, eds. *Oxford Dictionary of Science*, Fifth Edition. Oxford: Oxford University Press, 2005.
- de Ronde, Christian. "Interpreting The Quantum Wave Function in Terms of 'Interacting Faculties'." *PhliSci Archives* (December 3, 2007), <http://philsci-archive.pitt.edu/archive/00003691/> (accessed September 14, 2008)
- Deutsch, David. "Quantum Theory, the Church-Turing Principle and the Universal Quantum Computer." *Proceedings of The Royal Society of London, A*, 400 (1985), <http://coblitz.codeen.org:3125/citeseer.ist.psu.edu/cache/papers/cs/13701/http:zSz zSzwww.qubit.orgzSzresourcezSzdeutsch85.pdf/deutsch85quantum.pdf> (accessed February 25, 2008)
- Einstein, Albert, Boris Podolsky, and Nathan Rosen. "Can Quantum Mechanical Description of Physical Reality Be Considered Complete?" *Physical Review* 47 (May 1935): 777-780.
- Esfeld, Michael, "Do Relations Require Underlying Intrinsic Properties? A Physical Argument for Metaphysics of Relations," *International Journal for Ontology and Metaphysics*, 4 (2003), <http://www.unil.ch/webdav/site/philo/shared/DocsPerso/EsfeldMichael/2003/Metaphysica03.pdf> (accessed September 12, 2008)
- Filk, Thomas. "Relational Interpretation of the Wave Function and a Possible Way Around Bell's Theorem," *International Journal of Theoretical Physics*, 45, no. 6 (2006), <http://arxiv.org/abs/quant-ph/0602060> (accessed August 6, 2008)
- Ghirardi, Giancarlo "Collapse Theories," *The Stanford Encyclopedia of Philosophy*. Edited by Edward N. Zalta, Stanford: Metaphysics Research Lab (2007), <http://plato.stanford.edu/entries/qm-collapse/> (accessed September 25, 2008)
- , Rimini, A. and Weber, T., "Unified Dynamics for Microscopic and Macroscopic Systems." *Physical Review D* 34, (1986), <http://www.qpt.org.uk/index3.php?id=5&id2=17> (accessed April 13, 2008)

- Gödel, Kurt. "Gödel to Rappaport," *Collected Works*. Edited by Solomon Feferman, John W. Dawson, Jr. no. 5. Oxford: Clarendon Press, 2003.
- Gödel, Kurt, "A Remark about the Relationship Between Relativity Theory and Idealistic Philosophy" *Albert Einstein, Philosopher-Scientist*. Edited by P. A. Schilpp, La Salle: Open Court, 1949.
- Greene, Brian, *The Fabric of the Cosmos*. New York: Vintage Books, 2005.
- Gustafson, K. "Bell and Zeno," *International Journal of Theoretical Physics*, 44, no. 11 (2005): 1.
- Hagar, Amit. "Quantum Computing," *The Stanford Encyclopedia of Philosophy*. Edited by Edward N. Zalta, Stanford: Metaphysics Research Lab (2007), <http://Plato.stanford.edu/entries/qt-quantcomp/> (accessed August 17, 2008)
- , and Meir Hemmo. "Explaining the Unobserved ---- Why Quantum Mechanics Ain't Only About Information." *Foundations of Physics* 36, no. 9 (September 2006), <http://web.ebscohost.com.libaccess.sjlibrary.org/ehost/pdf?vid=3&hid=21&sid=f13271bc-b3ae-4cc4-8422-32eb0e046bda%40sessionmgr2> (accessed August 2, 2008)
- Healey, Richard, *The Philosophy of Quantum Mechanics: An Interactive Interpretation*, Cambridge: Cambridge University Press, 1989.
- . "Holism and Nonseparability in Physics," *The Stanford Encyclopedia of Philosophy*. Edited by Edward N. Zalta, Stanford: Metaphysics Research Lab (2004), <http://Plato.stanford.edu/entries/physics-holism/> (accessed July 20, 2008)
- . "Tim Maudlin: *The Metaphysics Within Physics*" *Notre Dame Philosophical Reviews* (February 2008), <http://ndpr.nd.edu/review.cfm?id=12283> (accessed March 29, 2008)
- Heisenberg, Werner, *Physics and Philosophy: The Revolution in Modern Science*. New York: Harper and Row, 1958.
- . "The Nature of Elementary Particles," *Interpreting Bodies: Classical and Quantum Objects in Quantum Physics*. Edited by E. Castellani. Princeton: Princeton University Press, 1998.
- Held, Carsten. "The Kochen-Specker Theorem." *The Stanford Encyclopedia of Philosophy*. Edited by Edward N. Zalta, Stanford: Metaphysics Research Lab (2006), <http://Plato.stanford.edu/entries/kochen-specker> (accessed April 13, 2008)

- Henson, Joe. "Comparing Casuality Principles." *Studies in the History and Philosophy of Science, Part B: Studies in History and Philosophy of Modern Physics* 36, no. 3 (September 2005): 519-543.
- Herbert, Nick *Quantum Reality*. New York: Anchor, 1985.
- Hilgevoord, Jan. "The Uncertainty Principle," *The Stanford Encyclopedia of Philosophy*. Edited by Edward N. Zalta, Stanford: Metaphysics Research Lab (2006), <http://Plato.stanford.edu/entries/qt-uncertainty/> (accessed August 16 , 2008)
- Honderich, Ted, editor, *The Oxford Companion to Philosophy*, Second Edition. Oxford: Oxford University Press, 2005.
- Hunting, Brad, and David Mertz, "Introduction to Quantum Computing," *IBM developerWorks* (September 1, 2001), <http://www.ibm.com/developerworks/linux/library/l-quant.html> (accessed August 18, 2008)
- Itano, W. M., D.J.Heinsen, and D.J.Wineland, "Quantum Zeno Effect," *Physical Review*, no. 51 (1990), http://prola.aps.org/abstract/PRA/v41/i5/p2295_1 (accessed February 2, 2008)
- Johnston, Hamish, "Anton Zeilinger Scoops First Issac Newton Medal," *physicsworld.com*, <http://physicsworld.com/cws/article/news/31379> (accessed August 2, 2008)
- Karakostas, Vassilios "Forms of Quantum Nonseparability and Related Philosophical Consequences," *Journal for General Philosophy of Science*, 35 (2006), http://philsci-archive.pitt.edu/archive/00002152/01/V.E._KARAKOSTAS.doc (accessed October 4, 2008)
- Katz, Jerrold, "What Mathematical Knowledge Could Be," *Mind, New Series*, 104, no. 415, (Jul., 1995), <http://www.jstor.org/pss/2254639> (accessed June 7,2008)
- Kochen, Simon, Ernst Specker, "The Problem of Hidden Variables in Quantum Mechanics," *Indiana University Mathematics Journal*, no. 1 (1968), <http://www.iuj.indiana.edu/IUMJ/dfulltext.php?year=1968&volume=17&artid=17004> (accessed April 12, 2008)
- Kouznetsov, D., H.Oberst, "Reflections of Waves from a Ridged Surface and the Zeno Effect," *Optical Review*, no. 12 (2005), <http://www.springerlink.com/content/b02m452484006tu1/> (January 29, 2008)
- Krauss, Lawrence M. *Hiding in The Mirror, The Mysterious Allure of Extra Dimensions, From Plato to String Theory and Beyond*. New York: Penguin Books, Ltd., 2005.

- Krips, Henry. "Measurement in Quantum Theory," *The Stanford Encyclopedia of Philosophy*. Edited by Edward N. Zalta, Stanford: Metaphysics Research Lab (2007), <http://Plato.stanford.edu/entries/qt-measurement/#EndCopMon> (accessed August 17, 2008)
- Kuriki, Gershon, "Zeno's Paradox Reversed: Watching a Flying Arrow Increase Its Speed" *Science News* (June 5, 2000), <http://www.sciencedaily.com/releases/2000/06/000602074805.htm> (accessed June 16, 2008)
- Landauer, Rolf "Information Is Physical," *Physics Today* (May 1991): 23-29.
- Laudisa, Federico and Carlo Rovelli, "Relational Quantum Mechanics," *The Stanford Encyclopedia of Philosophy*. Edited by Edward N. Zalta, Stanford: Metaphysics Research Lab (2007), <http://Plato.stanford.edu/entries/qm-relational/> (accessed July 26, 2008)
- Leng, Mary, "Mark Balaguer, Platonism and Anti-Platonism," *Bulletin of Symbolic Logic*, 8, no.4 (2002): 516-518.
- Loewer, Barry. "Copenhagen versus Bohemian Interpretations of Quantum Theory." *The British Journal for The Philosophy of Science* 49, no. 2 (June 1998), <http://bjps.oxfordjournals.org/cgi/reprint/49/2/317> (accessed April 5, 2008)
- Maudlin, Tim, *Quantum Nonlocality and Relativity*, Second Edition. Oxford: Blackwell Publishers, 2002.
- . *The Metaphysics Within Physics*. Oxford: Oxford University Press, 2007.
- McKay, David, *Information Theory, Inference, and Learning Algorithms* (2003), <http://www.cs.iastate.edu/~honavar/infotheorybook.pdf> (accessed August 1, 2008)
- McMahon, David *Quantum Mechanic DeMystified, A Self Teaching Guide*. New York: McGraw-Hill, 2006.
- Majid, Shahn *Faces of Mathematics*, <http://www.ma.hw.ac.uk/~ndg/fom/majidqu.html> (accessed June 22, 2008)
- Megill, Norman. "Hilbert Space Explorer Home Page," (December 2007), <http://us.metamath.org/mpegif/mmhil.html> (accessed April 5, 2008)
- Richard D. Mohr, "Number Theory in Plato's Republic VII and Philebus" *Isis*, Vol. 72, No. 4 (1981), [/links.jstor.org/sici?sici=0021-](http://links.jstor.org/sici?sici=0021-)

1753%28198112%2972%3A4%3C620%3ATNTIPR%3E2.0.CO%3B2-V
(accessed June 10, 2008)

Niiniluoto, Ilkka, "Scientific Progress," *The Stanford Encyclopedia of Philosophy*. Edited by Edward N. Zalta, Stanford: Metaphysics Research Lab (2007),
<http://plato.stanford.edu/entries/scientific-progress> (accessed July 20, 2008)

Peat, F. David, *Einstein's Moon, Bell's Theorem and the Curious Quest for Quantum Reality*. Chicago: Contemporary Books, 1990.

Penrose, Roger. *The Road to Reality*. London: Alfred A. Knopf, 2004.

Physics, School of University of New South Wales (Sydney): 1, "The Planck Scale: Relativity Meets Quantum Mechanics Meets Gravity." (2005),
http://www.phys.unsw.edu.au/einsteinlight/jw/module6_Planck.htm (accessed May 25, 2008)

Plotnitsky, Arkady "A New Book of Numbers: On the Precise Definition of Quantum Variables and the Relationships between Mathematics and Physics in Quantum Theory," *Foundations of Physics*, 36, no. 1 (January 2006): 53–54.

Popper, Karl, *The World of Parmenides, Essays on the Presocratic Enlightenment*. New York: Routledge, 1998.

Puthoff, H.E., "Quantum Fluctuations: a New Rosetta Stone of Physics,"
<http://ldolphin.org/zpe.html> (accessed June 10, 2008)

Randall, Lisa. *Warped Passages Unraveling The Mysteries of The Universe's Hidden Dimensions*. New York: HarperCollinsPublishers, 2005.

Ray-Murray, Fergus. "Quantum Entanglement and Causality,"
<http://fergusmurray.members.beeb.net/Causality.html> (accessed March 12, 2008)

Schrodinger, Ewin, "What Is an Elementary Particle" *Interpreting Bodies*. Edited by E. Castelani, Princeton: Princeton University Press, 1998.

Sedgewick, Robert, and Kevin Wayne. "Introduction to Programming in Java,"
<http://www.cs.princeton.edu/introcs/75universality/> (accessed February 25, 2008)

Sedley, David. "Platonic Causes." *Phronesis* 43, no. 2 (July 1998): 114-132.

Shannon, Claude E., "A Mathematical Theory of Communication," *Bell System Technical Journal* no.27, (July, October, 1948): 379-423, 623-656.

Sicard, Andrés; Vélez, Mario; Ospina, and Juan. "A Possible Hypercomputational Quantum Algorithm," *Quantum Information and Computation III*, SPIE Defense

- and Security Symposium. (2005),
<http://www.citebase.org/abstract?id=oai%3AarXiv.org%3Aquant-ph%2F0406137>
 (accessed February 25, 2008)
- Siegfried, Tom. *The Bit and The Pendulum, From Quantum Computing to M Theory --- The New Physics of Information*. New York: John Wiley & Sons, Inc., 2000.
- Silberstein, Michael, W.M. Stuckey, and Michael Cifone, "An Argument for 4D Blockworld from a Geometric Interpretation of Nonrelativistic Quantum Mechanics" *PhilSci Archives* (2007) http://philsci-archive.pitt.edu/archive/00003214/01/BW_from_NRQM.pdf (accessed March 12, 2008)
- Smith, D.W. Smith, A. Thomasson (ed.) "Consciousness of Abstract Objects." *Phenomenology and Philosophy of Mind*, New York: Oxford University Press, 2005.
- Smolin, Lee, *The Trouble With Physics*. New York: Houghton Mifflin Company, 2006.
- . *Three Roads to Quantum Gravity*. New York: Basic Books, 2001.
- Smyth, Richard, Reviewed work: *Causation, A Realist Approach*, *Nous*, 27, no. 1. (March 1993), <http://links.jstor.org/sici?sici=0029-4624%28199303%2927%3A1%3C91%3ACARA%3E2.0.CO%3B2-0> (accessed August 5, 2008)
- Suarez, Antoine, A. Stefanov, H. Zbinden, and N. Gisin, "Is There a Time Ordering Behind Nonlocal Correlations?" *Quantum Philosophy Theories* (2007), http://www.bioprodownloads.com/pdf/ResearchStudy_Oct20-01_RealTimeOrdering.pdf (accessed August 2, 2008)
- Summons, Dan "What is the Schrodinger Equation?" <http://www.physlink.com/Education/AskExperts/ae329.cfm?CFID=22564684&CFTOKEN=14110569> (accessed September 14, 2008)
- Tegmark, Max, "The Mathematical Universe," *Foundations of Physics*, 38, no. 2 (February, 2008), <http://web.ebscohost.com.libaccess.sjlibrary.org/ehost/detail?vid=6&hid=113&sid=9e3bcdd0-80a7-45d0-b231-8e8a69f95a9c%40sessionmgr108> (accessed May 25, 2008)
- Tieszen, Richard, "Consciousness of Abstract Objects," *Phenomenology and Philosophy of Mind*. Edited by D.W. Smith and A. Thomasson, New York: Oxford University Press, 2005.

- . “Mathematical Realism and Transcendental Phenomenal Realism,” *Phenomenology and Mathematics* (forthcoming).
- Timpson, Christopher G. “The Application of Shannon Information in Quantum Mechanics and Zellinger's Foundation Principle.” *Philosophy of Science* 70, no. 5 (December 2003), <http://web.ebscohost.com.libaccess.sjlibrary.org/ehost/detail?vid=5&hid=115&sid=37df67b2-0fe9-4b37-a063-cf61f40e2830%40sessionmgr104> (accessed August 1, 2008)
- Tooley, Michael. *Causation, a Realist Approach*. New York: Clarendon Press, Oxford University Press, 1987.
- Tumulka, Roderich, “On Spontaneous Wave Function Collapse and Quantum Field Theory” (2005), <http://arxiv.org/abs/quant-ph/0508230> (accessed June 12, 2008)
- Weinstein, Alan, “Wave Function Collapse, Quantum Reality, EPR, Bell’s Theorem, and All That.” *CiteSeerx*, The University of Pennsylvania (2007), http://citeseer.ist.psu.edu/weinstein96wave_function.html (accessed May 12, 2008)
- Weisstein, Eric W. “Ergodic Theory,” *Wolfram MathWorld* (2008), <http://mathworld.wolfram.com/ErgodicTheory.html> (accessed September 10, 2008)
- Wheeler, John. “Information, Physics, Quantum: The Search for Links.” *Feynman and Computation*. Edited by J.G.Hey, Reading: Persus Books, 1999.
- Whitehead, Alfred North Whitehead, *Process and Reality: An Essay On Cosmology*. New York: Free Press, 1929.
- Wikimedia Foundation, Inc. “John Von Neumann,” (2008), http://en.wikipedia.org/wiki/Von_Neumann#Quantum_mechanics (accessed July 19, 2008)
- Wilce, Alexander “Quantum Logic and Probability Theory,” *The Stanford Encyclopedia of Philosophy*. Edited by Edward N. Zalta, Stanford: Metaphysics Research Lab (2006), <http://Plato.stanford.edu/entries/qt-quantlog/> (accessed September 27, 2008)
- Yourgrau, Palle, *A World Without Time*. Cambridge: Basic Books, 2005.
- Zeilinger, Anton “Experimental Quantum Teleportation,” *Nature* 390 (December 1997). http://books.google.com/books?id=_JnrtbEGDNAC&pg=RA1-PA40&lpg=RA1-PA40&dq=%22Anton+Zeilinger,+%E2%80%9CExperimental+Quantum+Teleportation,%E2%80%9D+%22&source=bl&ots=kLp2b7Rsnt&sig=nBsmczwoUzI82

uPkmOZ2Isz-RvI&hl=en&ei=jp7PSZbcF-nlnQeLi6njCQ&sa=X&oi=book_result&resnum=2&ct=result#PRA1-PA40,M1
(accessed February 16, 2008)

Zukowski, Marek and Caslav Brukner, "Bell's Theorem for General N-Qubit states,
"Physical Review Letters, n, 88 210401 (2002), http://xxx.sissa.it/PS_cache/quant-ph/pdf/0102/0102039v3.pdf (accessed April 12, 2008)