A New Foundation for Standard Quantum Theory

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Abstract

This article presents a new way of looking at and understanding quantum physics through the lens of a novel framework. It addresses core issues of realism, locality, and measurement. It proposes a general quantum ontology consisting of two field-like entities, called W-state and P-state, that respectively account for the wave- and particle-like aspects of quantum systems. Unlike Bohmian mechanics, however, it does not take the conjunction of wave and particle literally.

W-state is a generalization of the wavefunction, but has ontic stature and is defined on the joint time-frequency domain. It constitutes a non-classical local reality, consisting of superpositions of quantum waves writ small. P-state enforces entanglement obligations and mediates the global coordination within quantum systems required to bring about wavefunction collapse in causal fashion consistent with special relativity.

The framework brings quantum theory much closer to general relativity; the ontological foundations of the two share common language, concepts, and principles. It explains the phenomenology of standard quantum theory, but offers a sensible alternative to the Copenhagen dispensation, which actively discourages - indeed, oracularly proscribes - inquiry that seeks to explain quantum mechanics more deeply than the fact that the mathematical formalism works.

Contents

1 Introduction

1.1 Quantum Reality: W-state and P-state

The ontology of quantum systems is envisaged as a pair of two field-like entities, called W-state and P-state, that are distributed in the four-dimensional space-time of special relativity. W-state is essentially an ontic[1] conception of the wavefunction and accounts for the wave-like behavior of quantum systems (the simplest types of which are generically called *quantons*). For the most part, W-state evolves deterministically, much like in the Schrödinger and Dirac equations. P-state dynamics, by contrast, are intricately non-local and depend sensitively on the outcomes of measurement events. P-state enforces entanglement obligations and mediates the global coordination within quantons required to bring about wavefunction collapse in causal fashion consistent with special relativity. P-state is necessary to account for the particle-like behavior of quantons, as well as strong measurement outcome correlations that cannot be explained by local hidden variables theories. It is the missing link that gives the completion of quantum state description that W-state alone cannot provide[2].

W-state and P-state jointly constitute the ontology of individual quantum systems. A primary focus of the technical development that follows is the causal dynamic structure of W-state and P-state.

1.2 Measurement Problem

Quantum physics is governed by two altogether different dynamics principles, namely Rule 1[3] (deterministic evolution of the wavefunction) and Rule 2 (wavefunction collapse precipitated by measurement events). The dichotomy implicitly countenances the notion of two qualitatively different forms of interaction between quantons and their surroundings. Rule 1 interactions involve forces of a simple kind that are conservative in nature and mesh smoothly with the W-state dynamics. Rule 2 interactions, by contrast, involve forces of a fitful, disruptive, and irreversible character that cause the W-state to change non-deterministically.

In the new framework, measurement events are perfectly ordinary physical processes and can arise from interactions with surrounding systems of any size - not just large classical instruments. The measurement problem is demystified and solved, once the causal dynamics of W-state and P-state become understood.

1.3 Ontology and Epistemology

From the outset, quantum mechanics has identified, drawn attention to, and stressed fundamental limitations on information that can be extracted from quantum systems through experimental intervention.

In the perspective of the new framework, a quanton is interrogated and manipulated through a sequence of contrived probings, as a result of which the W-state evolves in non-deterministic fashion governed statistically by the Born Rule. That evolution becomes manifest to the quanton's surroundings, which acquire partial information about the post-measurement W-state. From a statistical learning standpoint, the process through which information is acquired from the quanton can be modeled mathematically as a Kalman filter, Bayesian learning machine, or similar algorithmic construct. The retrospective picture of the W-state inferred from the process is informationally equivalent to the pre-measurement *epistemic* wavefunction.

In the new framework, the conventional epistemic understanding of quantum mechanics, including the Born Rule, follows as a deductive consequence of the deep ontic formulation in terms of W- and P-state. It thus rejects the historical stance of Bohr and Heisenberg, who maintained that the measurement outcomes themselves represent the deepest level of quantum reality [11].

Observations extracted from experiment correlate strongly with, *but do not literally or completely represent*, post-measurement W-state. As a simple example, consider a position measurement, for which the observable is a single number (nominal position). That correlates with a dramatic narrowing of the spatial extent of the W-state, but the W-state does not collapse literally to a single point of zero spatial extent, as that would violate the uncertainty principle.

The new framework recognizes two forms of uncertainty. Epistemic uncertainty is what Heisenberg identified and described through the microscope thought experiment. Ontic uncertainty pertains to physical limitations on

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[1] *Ontic* meaning in contradistinction to the mainstream view, which holds that the wavefunction is an epistemic construct.

[2] The new quantum framework affirms the incompleteness of the wavefunction that Einstein historically pointed out.

[3] This terminology is borrowed from Smolin [18]. It is similar to von Neumann's terminology of Type I and Type II processes.

the compressibility of W-state. As a general law, the W-state of a quanton cannot be pinched down to less than the Compton wavelength[4]. Ontic uncertainty is not a matter of ignorance, but of objectively real grayness or indefiniteness in states of nature.

1.4 Quantum Story Telling

The new framework promises to make physics intelligible once again. Quantum mechanics, as it is customarily portrayed and presented in textbooks, does not meet basic criteria of what it takes to tell a story: a story about how nature *is*. It is unable to answer questions of what, where, when, and how.

1.4.1 What?

After a century, there is no consensus among experts on the reality status or meaning of the underlying subject matter of quantum theory. It is not a settled matter even what an electron is. According to the historically dominant anti-realist Copenhagen dispensation, the term *electron* signifies not an objectively real microscopic entity, but merely a symbol appearing in the expression of a wavefunction, which is itself nothing more than a calculational device to predict statistical outcomes of experiments [8]. As Bohr famously said: "There is no quantum world. There is only an abstract quantum description. It is wrong to think the task of physics is to find out how nature *is*. Physics concerns what we can say about nature." [10]

1.4.2 Where? When?

Quantum mechanics is unable to provide a clear detailed picture of how Rule 1 and Rule 2 dynamics jointly play out in space-time in individual systems. It is sketchy because it is not rooted in any conception of local physical reality and laws founded thereupon. It has no well-known governing equation transparently equivalent to Newton's Second Law and thus cannot provide explanation in terms of local causation. Nor can it describe wavefunction collapse in terms of a spatio-temporal distribution of local measurement-like interactions with the environment. It speaks in entirely different language (*i.e.*, abstract Hilbert spaces) from classical physics [9]. The entire problem of quantum gravity has to do with the fact that quantum mechanics and general relativity do not mesh, because the two are such odd-couple opposites of one another [1, 19].

1.4.3 How?

Quantum mechanics cannot explain what measurement events are or delineate them as objectively real physical processes describable in straightforward physics terms. It offers no explanation for how wavefunction collapse is triggered, how it is coordinated globally within quantum systems that are distributed in space-time, or how an actual outcome that conforms statistically to a certain probability distribution is selected. Historically, the mainstream stance, ostensibly rooted in logical positivism, has been to dismiss such questions as meaningless by denying that the wavefunction has any ontic stature.

1.5 Realism

The term *realism* is a potential source of confusion [13] because it can have multiple meanings. In the quantum context, it has predominantly signified the contention that quantum systems *have* certain attributes, commonly thought of as hidden variables, that exist objectively at all times, irrespective of whether the system is being subjected to observation. It follows, the usual thinking goes, that those attributes pre-determine measurement outcomes. The antithesis of realism, in this technical sense, is anti-realism, which denies the existence of hidden variables and abides the aphorism that observation creates reality.

The new quantum framework can be said to be realist in a quite different and more basic sense of the word. It simply means that the logical structure of the theory recognizes the validity of, and enables the theory to answer, questions of what, where, when, and how. It is the opposite of anti-realism in the non-technical sense, which takes an agnostic or denialist stance on ontology and insists that such questions are *prima facie* meaningless.

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[4] This is a fuzzy lower bound on the spatial extent over which the local W-state is appreciably non-zero, not a hard inequality.

The new framework posits pre-measurement quantum state that consists of part wavefunction (W-state) and part hidden variables (P-state), but is unlike ordinary objects. P-state constrains the measurement outcome space, but the actual outcome within that space depends on pure chance. In this respect, the new framework dissents from realism in the aforementioned narrow sense of the term. As for observation creating reality, it holds that the act of measurement precipitates a synthesis of random information content (which goes by the term *innovation*) at the measurement site(s), which initiates a wavefunction collapse process. The structure of the theory is realist, in the less technical sense of the term, in that it provides a clear detailed picture of how the innovation is disseminated in fashion consistent with the strictures of non-local causality and makes possible a globally coordinated response within the quanton.

2 Q-1: Quantum Physics between Measurement Events

2.1 Classical and Quantum Ontology

2.1.1 Classical and Quantum Conceptions of Local Reality

In classical physics, local reality can be represented mathematically by tensor fields, *i.e.*, scalars, vectors, or higher-order tensors. In electromagnetic theory, for example, local reality is the combination of an electromagnetic field tensor and a current density 4-vector. In general relativity, it is the combination of space-time curvature and energy-momentum tensors. Tensors are collections of real-valued physical quantities that come with certain transformation methods that account for how different observers would describe the same underlying beable structures.

In the quantum realm, local reality is very different. Its wave-like part (W-state) consists of superpositions of quantum wave elements writ small. To appreciate what this means, it is necessary to illuminate fundamental differences between classical and quantum waves.

2.1.2 Classical Wave Ontology

In a classical wave, a physically real and mathematically real-valued tensor quantity oscillates at each point in space occupied by the wave. At certain times, it can be said objectively that that quantity is at a peak. At other times, it is zero. The physical reality of a classical system is the set of tensor values at the points it occupies.

Classical wave theory is built upon the mathematical foundation of Fourier analysis, which holds that functions defined on the space-time domain can be expressed in equivalent form in the wavenumber-frequency[5] domain, and vice versa. Mathematically, either representation is complete and convertible to the other. Physically, however, waves are emergent phenomena that arise from the collective properties[6] of tensor field values over finite regions of space (spanning at least several wavelengths). For this reason, the time domain is regarded as *ontically primary* in the classical realm, whereas the frequency domain is of secondary stature.

2.1.3 Quantum Wave Ontology

Consider the simplest abstraction of a quantum system, which is a pure quantum wave. Mathematically, it can be represented by a wavefunction, *viz.*,

$$\psi(\underline{x}, t) = e^{i\omega t} \tag{1}$$

Eq. 1 describes a wave, but one that has no crests, troughs, or zeros. The wavefunction expression on the right-hand side of Eq. 1 says nothing *about* physical reality at points at time t in isolation[7]. In fact, anything that can be said about states at t can be said about those at any other time. It is meaningful to speak only of the phase difference between wavefunction values at two different points. In this respect, the ontology of quantum waves is inherently *relational*[8] in nature.

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[5] For brevity, these will be referred to henceforth simply as the time and frequency domains.

[6] Classical waves are “crowd waves”, in a specific technical sense that is not true of quantum waves.

[7] Other than whether or not it is zero, which is not the case in Eq. 1 at any time.

[8] The word *relational* is used in many ways in quantum physics and philosophy of science, but a specific meaning applies here.

2.1.4 Reductionism

Reductionism is built into the structure of classical physical theory; it can be expressed semi-formally as:

$$P(\underline{x}_A, \underline{x}_B) = P_r(\sigma(\underline{x}_A), \sigma(\underline{x}_B), \underline{x}_A - \underline{x}_B) \tag{2}$$

The left-hand side of Eq. 2 represents any meaningful assertion, recognized as such within the logical structure of the theory, pertaining jointly to the physical states at points $\underline{x}_A$ and $\underline{x}_B$. The right-hand side of the equation indicates that the assertion can be reduced to a predicate, P_r, on the local states[9] in conjunction with the spatio-temporal interval between the points.

Eq. 2 gives expression to the conceptual primacy of local reality in classical physics. It indicates that classical physical theory can - indeed, *must* - be described entirely in terms of local states and the space-time fabric on which they reside. Alternatively interpreted, a whole can always be reduced to a sum of local parts, which exist meaningfully as such.

From the relational nature of local state in Eq. 1, it follows that the nature of being in the quantum realm is *not* reductionist.

2.1.5 Local Causality

The structure of classical physical theory is *locally causal* in that it admits only dynamics law such the state at any point depends only on the states at recent points in its aft light cone. It is noted that the concept of innovation, despite its contrafactual nature, plays an essential role in defining causal structure.

Experimental fact, such as Bell inequality violations, compels the conclusion that the causal structure of quantum theory is drastically different from that of classical physics. Quantum theory incorporates causality in a less restrictive form called *weak non-locality*, which is introduced in detail further on.

2.1.6 Determinism

Despite the metaphor of Newtonian physics as clockwork universe, determinism is *not* an essential facet of classical physics. There is nothing logically untenable about dynamics law that injects innovation; it amounts merely to attributing ostensibly stochastic phenomena to absolute randomness rather than classical ignorance.

2.2 W-state Ontology

2.2.1 Quantum Phase

In quantum physics, the meaning of complex-valued quantities, such as on the right-hand side of Eq. 1, is altogether different from that in classical physics. Complex-valued quantities are commonly used to represent classical waves, but only as a mathematical convenience to simplify analysis. In classical wave-theoretic application problems, the real part of the complex-valued quantity[10] represents the physical ontology of interest. In the quantum realm, the real and imaginary parts of the wavefunction expression have no physical significance.

According to Eq. 1, *quantum phase*, which is a distinctly non-classical concept by virtue of its relational nature, is constant on manifolds of constant time. This property uniquely defines the rest frame of the quantum wave. Phase differences are defined operationally in terms of superposition: If the states represented by the wavefunction at two different points were collocated[11], they would interfere constructively (destructively) if they are in phase (out of phase).

2.2.2 Superpositions of Quantum Waves

Consider next a Fourier combination of pure quantum waves, *viz.*,

$$\psi(\underrightarrow{x}) = \int \tilde{\psi}(\underrightarrow{k}) e^{i(\underrightarrow{k} \cdot \underrightarrow{x})}\, d\underrightarrow{k} \tag{3}$$

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[9] The spatial orientations of the local states are included in the tensor expressions $\sigma(\underline{x}_A)$ and $\sigma(\underline{x}_B)$.

[10] In the construction of the complex-valued quantity, the imaginary part is derived as the Hilbert transform of the real part.

[11] This is formalized as an *active transformation*.

which employs 4-vector notation $\underset{\rightarrow}{\underline{k}} \equiv (\underline{k}, \omega/c)$ and $\underset{\rightarrow}{\underline{x}} \equiv (\underline{x}, ct)$. Eq. 3 represents a set of wave components that intersect the point $\underset{\rightarrow}{\underline{x}}$ but have different velocities relative to an observer[12], who describes each component in terms of a wavenumber ($\underline{k}$) and frequency (ω). In Eq. 3, the phase of the wave component with coefficient $\tilde{\psi}(\underset{\rightarrow}{\underline{k}})$ is $\underset{\rightarrow}{\underline{k}} \cdot \underset{\rightarrow}{\underline{x}} = \omega t - \underline{k} \cdot \underline{x}$.

The summation in Eq. 3 signifies *superposition.* The wave components have definite amplitude ratios and phase shifts relative to one another at $\underset{\rightarrow}{\underline{x}}$, by virtue of their coexisting at that point.

2.2.3 Time-Frequency Representation of W-state

W-state consists of superpositions of quantum waves, *writ small.* This requires a slight modification of Eq. 3, *viz.*,

$$\psi(\underset{\rightarrow}{\underline{x}}) = \int \tilde{\psi}(\underset{\rightarrow}{\underline{k}}, \underset{\rightarrow}{\underline{x}}) e^{i(\underset{\rightarrow}{\underline{k}} \cdot \underset{\rightarrow}{\underline{x}})} \, d\underset{\rightarrow}{\underline{k}} \tag{4}$$

Eq. 4 is a generalization of Eq. 3, but with the important difference that $\tilde{\psi}$ depends on $\underset{\rightarrow}{\underline{x}}$ as well as $\underset{\rightarrow}{\underline{k}}$. It denotes a local Fourier transform.

Mathematically, the W-state at $\underset{\rightarrow}{\underline{x}}$ is represented definitively and completely[13] by $\tilde{\psi}$, which is regarded as a function defined on the time and frequency domains *jointly.* In the quantum realm, the joint time-frequency domain is considered ontically primary.

Whereas classical waves are emergent phenomena, quantum waves are irreducibly wave-like entities. Phase relationships between points are physically real in their own right and exist locally - therefore at well below wavelength scale. For this reason, quantum waves are said to have ontic stature *as waves.*

The $\underset{\rightarrow}{\underline{x}}$-dependence in $\tilde{\psi}(\underset{\rightarrow}{\underline{k}}, \underset{\rightarrow}{\underline{x}})$ allows the Fourier combinations of waves to bend and vary freely[14] throughout the regions of space-time occupied by a quanton. The $\underset{\rightarrow}{\underline{x}}$-dependence, however, precludes the inverse Fourier transform. It follows that the wavefunction, $\psi(\underset{\rightarrow}{\underline{x}})$, is remiss in that it contains less information than the set of Fourier coefficients, $\tilde{\psi}(\underset{\rightarrow}{\underline{k}}, \underset{\rightarrow}{\underline{x}})$, at $\underset{\rightarrow}{\underline{x}}$. Because the W-state itself is incomplete, the wavefunction can be said to be a doubly incomplete description of reality.

2.2.4 Rest Manifolds

The most important emergent aspect of W-state is the concept of *rest manifolds.* These are stacks of Cauchy manifolds[15] that are tangent to constant-time manifolds in the local rest frame, wherein the net momentum is zero, *viz.*,

$$\int \left| \tilde{\psi}(\underset{\rightarrow}{\underline{k}}, \underset{\rightarrow}{\underline{x}}) \right| \underline{k} \, d\underset{\rightarrow}{\underline{k}} = \underline{0} \tag{5}$$

in which $\underline{k}$ is the wavenumber 3-vector obtained from the 4-vector $\underset{\rightarrow}{\underline{k}}$ in the local rest frame.

Rest manifolds provide a generalized invariant definition of rest frame for quantons. A single rest manifold can be regarded as a "snapshot" of the quanton. Collectively, the manifolds, no two of which intersect, form a stack that fill 4D space-time and can be parametrized by a proper time of the whole quanton.

Rest manifolds are important because they provide a synchronization mechanism on which *non-local changes in the quanton W-state can be effected in fashion compatible with special relativity.* It is noted that rest manifolds are absolute (invariant) in that any two observers will agree on whether any two points are on the same manifold.

2.2.5 Quantum State

The totality of W-state on a rest manifold corresponds exactly to the concept of quantum state, $|\psi\rangle$, in standard quantum theory.

A general criterion governing the W-state dynamics is that it is square-integrable[16] on the rest manifolds, from which it follows that the set of realizable quantum states is a Hilbert space. Note that the interpretation of $|\psi\rangle$ in

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[12] Meaning a passive observer, in the sense of special relativity.

[13] $\tilde{\psi}(\underset{\rightarrow}{\underline{k}}, \underset{\rightarrow}{\underline{x}})$ represents only translational W-state, which is a complete description only for spinless quantons devoid of substructure.

[14] The variation arises from the external force environment. In the absence of any force, $\tilde{\psi}$ depends only on $\underset{\rightarrow}{\underline{k}}$.

[15] A *Cauchy manifold* is a 3D manifold in space-time, any two points on which are space-like separated.

[16] This formalizes the ontic form of the uncertainty principle into the structure of W-state.

terms of W-state ontology imparts to it a visualizable physicality that is remiss in conventional quantum theory, which leaves $|\psi\rangle$ as an irreducible abstraction impervious to any deeper comprehension. The new framework, by contrast, provides a mental picture of how $|\psi\rangle$ represents a slice of quantum reality that is distributed in space-time. In this respect, it is truly an *interpretation* of standard quantum theory[17].

As will be shown further on, the W-state can change discontinuously across a rest manifold *in toto*, with pre-measurement state on the aft side and post-measurement state on the fore side, reifying the notion of a quantum jump.

For any type of measurement interaction to which the quanton could conceivably be subjected, there corresponds a *spectral measure*[9] that can be derived from the pre-measurement W-state on the aft side of the rest manifold. The spectral measure maps each possible measurement outcome (eigenvalue) to the corresponding eigenspace of the W-state. In this respect, it can be said that all possibilities (potentia) are embedded in the pre-measurement W-state, although only one is actually selected.

2.2.6 W-state Current Density

From the W-state, a current density 4-vector, $\underrightarrow{J} \equiv (\underline{J}, c\rho)$, is readily derived, *viz.*,

$$\rho = \int\!\!\int \tilde{\psi}^*(\underrightarrow{k}', \underrightarrow{x})\tilde{\psi}(\underrightarrow{k}, \underrightarrow{x})e^{i\,(\underrightarrow{k}-\underrightarrow{k}')\cdot\underrightarrow{x}}\, d\underrightarrow{k}\, d\underrightarrow{k}{}' \tag{6a}$$

$$\underline{J} = \int\!\!\int \underline{\eta}(\underrightarrow{k}, \underrightarrow{k}')\, \tilde{\psi}^*(\underrightarrow{k}', \underrightarrow{x})\tilde{\psi}(\underrightarrow{k}, \underrightarrow{x})e^{i\,(\underrightarrow{k}-\underrightarrow{k}')\cdot\underrightarrow{x}}\, d\underrightarrow{k}\, d\underrightarrow{k}{}' \tag{6b}$$

in which the density, ρ, equates to the squared wavefunction amplitude, $|\psi|^2$, in the Born Rule. The density, integrated across any rest manifold, is unity.

Between measurement events, the continuity equation holds, *viz.*,

$$\Box \cdot \underrightarrow{J} = \nabla \cdot \underline{J} + \frac{\partial \rho}{\partial t} = 0 \tag{7}$$

which requires

$$\underline{\eta}(\underrightarrow{k}, \underrightarrow{k}') = \frac{c^2}{\omega + \omega'}(\underline{k} + \underline{k}') \tag{8}$$

in Eq. 6b.

2.3 W-state Dynamics and Causation

The formulation of W-state in the time-frequency domain imparts to quantum theory what was lost in the historic gestation of quantum mechanics: not only a clear definitive conception of local physical reality, but also dynamics laws driven by local causation.

2.3.1 Threads

The term *thread* signifies the concept of classical point particle trajectories, applied to the formulation of W-state structure and dynamics in the quantum realm. They can be thought of as similar in concept to the particle trajectories of Bohmian mechanics, but without particles as such in the W-state ontology. Instead, they signify paths of direct causal connectivity amongst local W-state components on different rest manifolds.

2.3.2 Thread Dynamics

In classical and quantum systems driven by conservative forces, particle dynamics are governed by a Lagrangian function, *viz.*,

$$L(\underline{x}, \dot{\underline{x}}) \tag{9}$$

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[17] Standard quantum theory meaning just the physics, not the standard *interpretation* of quantum theory.

in which $\underline{x}$ and $\dot{\underline{x}}$ respectively denote the position and velocity at a point on the trajectory. In general, the functional form of the Lagrangian depends on intrinsic attributes of the quanton (*e.g.*, mass, electric charge) and the force fields (*e.g.*, Coulomb attraction between electron and nucleus) driving the dynamics between measurement events.

The Lagrangian yields a dynamics equation in the form of Newton's Second Law, *viz.*,

$$\dot{\underline{p}} = \underline{F} \tag{10}$$

in which $\underline{p}$ is the momentum, *viz.*,

$$\underline{p} \equiv \frac{\partial L}{\partial \dot{\underline{x}}} \tag{11}$$

and F is the force acting on the thread, *viz.*,

$$\underline{F} \equiv \frac{\partial L}{\partial \underline{x}} \tag{12}$$

The Hamiltonian, *viz.*,

$$H \equiv \underline{p} \cdot \dot{\underline{x}} - L \tag{13}$$

yields the joint evolution of the position and momentum, *viz.*,

$$\dot{\underline{x}} = \frac{\partial H}{\partial \underline{p}} \tag{14a}$$

$$\dot{\underline{p}} = -\frac{\partial H}{\partial \underline{x}} \tag{14b}$$

Threads have well-defined position ($\underline{x}$) and momentum ($\underline{p}$), which jointly constitute thread kinematic state.

2.3.3 Thread Phase

Tangent to any point, $\underrightarrow{x}$, on a thread is the quantum wave component corresponding to $\tilde{\psi}(\underrightarrow{k}, \underrightarrow{x})$, in which $\underrightarrow{k}$ is directly proportional to the energy-momentum, $\underrightarrow{p} \equiv (\underline{p}, E/c)$, through Planck's constant, *viz.*,

$$E = \hbar\omega \tag{15a}$$

$$\underline{p} = \hbar\underline{k} \tag{15b}$$

At each point on the thread, the momentum, $\underline{p}$, is obtained from the solution of Eq. 14b, and E is the combination of rest and kinetic energy, *viz.*,

$$E = c(m^2c^2 + p^2)^{1/2} \tag{16}$$

The phase difference between the wave components tangent to the thread at points $\underline{x}_A$ and $\underline{x}_B$ is $\vartheta = S/\hbar$, where S is the action integral, *viz.*,

$$S \equiv \int_{\underline{x}_A}^{\underline{x}_B} L(\underline{x}, \dot{\underline{x}})\, dt \tag{17}$$

in which dt denotes increments of proper thread time.

There is a noteworthy difference between the classical and quantum Lagrangians. That the phase rate, ω, is physically consequential in the superposition patterns it produces implies that the Lagrangian in Eq. 17 must be absolute, whereas in classical mechanics, the Lagrangian is indeterminate to within an arbitrary additive constant.

2.3.4 Causal Structure of W-state Dynamics

To simulate the dynamic evolution of W-state, $\tilde{\psi}(\underrightarrow{k}, \underrightarrow{x})$ must be initialized for all $\underrightarrow{k}$ and $\underrightarrow{x}$ on a Cauchy manifold, $\mathcal{M}$[18]. The W-state at all points causally downstream of $\mathcal{M}$ is then obtained as:

$$\tilde{\psi}(\underrightarrow{k}, \underrightarrow{x}) = \int_{\mathcal{M}} G(\underrightarrow{k}, \underrightarrow{x}, \underrightarrow{k}', \underrightarrow{x}')\, \tilde{\psi}(\underrightarrow{k}', \underrightarrow{x}')\, d\underrightarrow{k}' d\underrightarrow{x}' \tag{18}$$

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[18] This need not be a rest manifold.

in which G denotes a Green's function. Eq. 18 states that W-state dynamics, in general, are linear.

Eq. 18 is centrally important to W-state ontology, which must be described in relational terms. Whereas superposition, as in Eq. 4, enables one to speak of amplitude and phase relationships between two threads by virtue of their intersecting at a point, Eq. 18 provides the basis for speaking of relationships among $\tilde{\psi}$ values at time-like separated points.

In principle, G captures completely the physics that governs the evolution of the quanton W-state until the next measurement event. Given G and initial conditions on a rest manifold, $\mathcal{M}$, $|\psi\rangle$ is determinate at future times, and the eigenstructure of the pre-measurement W-state enables the probability distribution of outcomes to be ascertained for any conceivable type of measurement process.

In this specific respect, the W-state is a complete description of deep quantum reality between measurements. The indefiniteness of dynamic attributes[19] (observables) is an objectively real feature of the interim state of nature. Bohr was right, although of course he never explained his reasoning in quite this way.

The W-state, as an ontic description of an individual system, is incomplete in that it cannot account for measurement outcome correlations with other quantons with which it is entangled. P-state is the supplementation of W-state required for a complete description that does account for the correlations. It is the missing element of reality that was correctly exposed in the EPR argumentation; Einstein was also right[20].

2.3.5 Physical and Geometric Optics Regimes

For $\hbar > 0$, the W-state dynamics in general are akin to physical optics, wherein diffraction effects are important, and Eq. 18 gives expression to Huygen's Principle. In the classical limit of $\hbar \to 0$, physical optics reduces to geometric optics, and the W-state dynamics reduce to a classical ensemble of independent particle trajectories.

Eq. 17, although conceptually important and noteworthy, holds exactly only in the geometric optics regime, wherein $\underline{x}_A$ and $\underline{x}_B$ are connected causally by only a single path. Feynman path summations generalize Eq. 17 to the physical optics regime. In that regime, only short threads (*i.e.*, locally tangent quantum waves) remain rigorously well-defined.

The term *thread* henceforth means short thread or long thread, depending on the context. The latter pertains to a pair of points separated by a finite time-like interval; the causal connectivity relations between W-state components at the two points become blurred over a bundle of paths whose phases sum coherently in the vicinity of the central "classical" path.

Feynman paths are subject only to the restriction[21] of being world lines, any two points on which are time-like separated. To evaluate a path integral in the general case, an arbitrary path from $\underline{x}_A$ to $\underline{x}_B$ is discretized as a sequence of waypoints. Any two consecutive waypoints are connected by a common short thread, the action along which can be evaluated using Eq. 17. In transferring from one thread segment to the next, the phase difference between the incoming and outgoing threads is determinate by virtue of their intersecting at the intervening waypoint, as was noted for Eq. 3.

2.3.6 Schrödinger Equation

The evolution of the quantum state, $|\psi\rangle$, over a succession of rest manifolds is governed by the Schrödinger and Dirac equations, *viz.*,

$$\frac{d}{dt}|\psi\rangle = -i/\hbar \cdot H\,|\psi\rangle \tag{19}$$

in which H is the Hamiltonian in Heisenberg matrix form[22]. H can be derived from G, and vice versa.

With the Schrödinger equation now on an ontic footing, its mystique dissolves. Historically, it was discovered through heuristic analogy to the Hamiltonian formulation of classical mechanics. The analogy, of course, proved successful and became part of the received wisdom and practical working knowledge of 20th-century physics, which moved on to less philosophical priorities.

In classical mechanics, the Hamiltonian formulation is derived from Newton's Laws, with the Lagrangian formulation as an intermediate step. In the quantum realm, however, the Schrödinger equation, by itself without

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[19] Unless the W-state is already in an eigenstate of the attribute being measured.

[20] Einstein was ultimately wrong about determinism and locality, but Bohr was even more wrong to dismiss the issues.

[21] Popular descriptions and illustrations often overstate the "crazy" character of Feynman paths.

[22] This is different from, but related to, the Hamiltonian in Eqs. 13-14.

connection to any underlying ontology, defies easy reverse engineering and reformulation backwards to more basic form akin to Newton's Second Law.

To model the W-state physics directly in terms of the Green's function, G, is a through-and-through quantum approach. By contrast, the traditional approach of first quantization, which involves replacement of classical dynamic variables with operator counterparts, is a particle-centric approach[23].

2.3.7 Classical Limit

In the limit of $\hbar \to 0$, the theory of W-state ontology and dynamics reduces seamlessly to classical physics. The thread kinematics coincide with the particle trajectories in a classical ensemble, and single-particle trajectories follow from highly localized W-state initializations. The quantum and classical realms are united under a single formalism and theoretical roof.

At least two effects that are important in the quantum realm disappear in the classical limit of $\hbar \to 0$. Phase rate becomes infinite. Interference and diffraction effects disappear, and Eq. 17 no longer applies. The Lagrangian remains relevant only in the expression of Newton's Second Law, wherein it is indeterminate to within an additive constant. However, rest manifolds are still mathematically well-defined and remain important in the context of non-locality and measurement processes.

In the Aharonov-Bohm (AB) effect, interference effects depend directly on the electromagnetic potential field $(\boldsymbol{A}, \phi/c)$. The effects are gauge-invariant, but cannot be derived from the electromagnetic fields ($\boldsymbol{E}$ and $\boldsymbol{B}$) alone. Alternatively interpreted, the AB effect cannot be explained without explicit incorporation of the potential field into the Lagrangian [20]. In the quantum realm, $(\boldsymbol{A}, \phi/c)$ thus has ontic stature in its own right, but that ceases to be apparent in the limit of $\hbar \to 0$. The electromagnetic dependence in the Lagrangian seamlessly reduces to local interaction with the electromagnetic field tensor and can be expressed entirely in terms of $\boldsymbol{E}$ and $\boldsymbol{B}$, consistent with classical electromagnetic theory.

It is noted that $\hbar \to 0$ is just one aspect of the classical limit. A second aspect pertains to conditions (*e.g.*, large quantum numbers) under which quantons, within the quantum theory with finite $\hbar$, behave classically.

2.3.8 Free Quanton Dynamics

In the simple scenario of a free quanton, the Lagrangian function is translationally invariant and equates to the energy, E. The solutions of the Hamilton equations are straight-line trajectories with constant velocity, and the rest manifolds are stacks of flat 3D Cauchy manifolds. In the general case amidst non-zero force fields, by contrast, the thread trajectories are curvilinear[24], and the rest manifolds are warped.

With a translationally invariant Lagrangian, the W-state components are independent of $\underrightarrow{x}$, and Eq. 3 holds. In this scenario, the wavefunction, ψ, *is* complete and can be regarded as having ontic stature in that the W-state, $\tilde{\psi}$, can be obtained from the inverse Fourier transform from the time to the frequency domain.

In practice, solutions of the Schrödinger equation, such as for the hydrogen atom, are crafted as static combinations of pure waves that satisfy the boundary conditions of a Sturm-Liouville problem. At each point in space occupied by the atomic electron, these are the quantum wave components locally tangent to the long threads, which are Keplerian elliptic orbits. The straight-line trajectories are not true long threads; they are merely artifacts of how the Keplerian orbit threads fit together in eigenstate solutions.

2.4 Spin

In the new quantum framework, spin is regarded as anisotropic local W-state.

2.4.1 Spin Up, Spin Down

Consider the simple case of W-state, for a pure wave in its rest frame, described as "spin up" with respect to the $+\hat{z}$-axis. The application of the rotation operator, $\boldsymbol{R}(\hat{z}, \vartheta)$, to the W-state signifies an active transformation,

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[23] Indeed, the Copenhagen view implicitly regards the ontology (even if it does not call it that) as primarily particle-like.

[24] In the physical optics regime, it is more correct to say that the short thread elements form a curvilinear mosaic.

which yields a physical rotation of the original W-state (operand) about the $+\hat{z}$-axis through angle ϑ. The rotated spin up state is related to the unrotated through a positive phase shift, *viz.*,

$$\boldsymbol{R}(\hat{z},\vartheta)\cdot\uparrow_{\hat{z}}=e^{is\vartheta}\cdot\uparrow_{\hat{z}} \tag{20}$$

in which s is a spin quantum number. The rotated spin down state is related to the unrotated through a negative phase shift, *viz.*,

$$\boldsymbol{R}(\hat{z},\vartheta)\cdot\downarrow_{\hat{z}}=e^{-is\vartheta}\cdot\downarrow_{\hat{z}} \tag{21}$$

Any two W-states satisfying the aforementioned description of "spin up" are the same modulo a multiplicative scalar, and similarly for spin down.

2.4.2 Superposition of Spin Up and Spin Down

Consider a reference spin up state, $\uparrow_{\hat{z}}$, and a reference spin down state, $\downarrow_{\hat{z}}$, both of unit amplitude. The superposition of the two is aligned along a geometric axis (which may be labeled $+\hat{x}$) perpendicular to $\hat{z}$, *viz.*,

$$\uparrow_{\hat{z}}+\downarrow_{\hat{z}}=\uparrow_{\hat{x}} \tag{22}$$

There is no absolute number that can be ascribed to the phase difference between the up and down reference states (let alone their individual phases), but the phase difference finds physical expression in the particular geometric axis on which the superposition is aligned.

2.4.3 Spin Quantum Number

Consider rotation of the superposition about about the $+\hat{z}$-axis through angle ϑ. The rotation operator is distributive, from which one obtains:

$$e^{is\vartheta}\cdot\uparrow_{\hat{z}}+e^{-is\vartheta}\cdot\downarrow_{\hat{z}}=\boldsymbol{R}(\hat{z},\vartheta)\cdot\uparrow_{\hat{x}} \tag{23}$$

In the case of $\vartheta=2\pi$, $\uparrow_{\hat{x}}$ undergoes rotation through a full geometric revolution, which returns to a state of spin aligned along the $+\hat{x}$-axis. It follows that $\boldsymbol{R}(\hat{z},2\pi)$ must be a scalar, and in conjunction with Eq. 22 that the phase factors on the left-hand side of Eq. 23 must be equal. The spin quantum number, s, must therefore be either integer or half-integer. This corroborates empirical fact that nature hosts two types of quantons: (*i*) fermions, for which s is half-integer, and (*ii*) bosons, for which s is whole integer.

For bosons, rotation through $\vartheta=2\pi$ restores the original state. For fermions, rotation through $\vartheta=2\pi$ yields the negative of the original state; rotation through $\vartheta=4\pi$ restores the original state.

2.4.4 Spin Dynamics and Flexure

For spinless quantons ($s=0$), the W-state is isotropic, and its dynamics depend only on translational state. Quantons with spin additionally have rotational state, which consists of position (spin axis alignment) and velocity. Spin axis alignment can be visualized as a vector arrow strapped onto each thread. The translational and rotational components of thread state jointly evolve under a single Hamiltonian.

In the new framework, spin is local, and spin fields can exhibit *flexure*, *i.e.*, spin alignment variation within quantons. This allows for spin-orbit coupling to play out locally through the dynamics laws. In conventional quantum theory, by contrast, quanton spin is monolithic and described entirely by two numbers: spin magnitude (s) and projection (s_z) onto any one geometric axis.

2.5 Systems of Identical Quantons

The theoretical development up to this point has encompassed only single quantons. Its extension to systems of multiple quantons is now addressed.

2.5.1 Multi-Quanton W-state

The multi-quanton W-state at a given point consists of a list of single-quanton states $\tilde{\psi}_1$, $\tilde{\psi}_2$, $\tilde{\psi}_3$, etc. $\tilde{\psi}_1$ can be regarded as the state of the quanton with the greatest presence at the point, $\tilde{\psi}_2$ that of the quanton with the second greatest presence, and so forth. In general, the list is indefinitely long, in principle encompassing all quanton instances in the universe, but only finitely many quantons, with some manner of roll-off, have appreciably non-zero presence at any point.

Multi-quanton W-state is a superposition of *pure* states of the form:

$$1 \otimes 2 \otimes 3 \otimes \ldots \tag{24}$$

in which individual instances of the quantons are considered distinct and labeled. In the notation of Eq. 24, quanton instance 1 instantiates $\tilde{\psi}_1$, instance 2 instantiates $\tilde{\psi}_2$, and so forth. '$\otimes$' denotes collocation of two or more quantons of the same type.

2.5.2 Tight Superpositions

Pure states serve as building blocks of mathematical expression of multi-quanton W-state. However, only certain types of combinations of pure states, called *tight superpositions*, can represent actual multi-quanton states.

For bosons, tight superpositions are sums of all permutations of a reference pure state, *e.g.*, for $N = 3$:

$$1 \otimes 2 \otimes 3 + 2 \otimes 3 \otimes 1 + 3 \otimes 1 \otimes 2 + 3 \otimes 2 \otimes 1 + 2 \otimes 1 \otimes 3 + 1 \otimes 3 \otimes 2 \tag{25}$$

In Eq. 25, the first term, $1 \otimes 2 \otimes 3$, serves as the reference pure state. For a system of N identical quantons, there are $N!$ pure states equivalent to any reference through a permutation.

For fermions, tight superpositions are the same as in Eq. 25, except that odd-order permutation terms are negated. For $N = 3$:

$$1 \otimes 2 \otimes 3 + 2 \otimes 3 \otimes 1 + 3 \otimes 1 \otimes 2 - 3 \otimes 2 \otimes 1 - 2 \otimes 1 \otimes 3 - 1 \otimes 3 \otimes 2 \tag{26}$$

2.5.3 Spin-Statistics Theorem

It is empirical fact that bosons have integer spin and conform to tight superpositions of the form in Eq. 25, and that fermions have half-integer spin and conform to Eq. 26. The Pauli spin-statistics theorem (PSST) provides theoretical explanation in terms of conventional quantum theory. In terms of the new framework, PSST relies on the postulate[25]:

$$\boldsymbol{R}(\hat{n}, 2\pi) \cdot (1 \otimes 2 \otimes 3 + 2 \otimes 3 \otimes 1 + 3 \otimes 1 \otimes 2) = \pm(3 \otimes 2 \otimes 1 + 2 \otimes 1 \otimes 3 + 1 \otimes 3 \otimes 2) \tag{27}$$

The left-hand side of Eq. 27 signifies the sum of the even-order permutations of a reference pure state, rotated through a full revolution about some arbitrary geometric axis ($\hat{n}$). The right-hand side contains the sum of the odd-order permutations; the + sign (− sign) applies to bosons (fermions).

From Eq. 27, in conjunction with the results for application of the rotation operator to spin states, it follows that rotation of any multi-quanton system through full revolution about any geometric axis reproduces the original W-state, with phase factor +1 for bosons and fermions alike.

To make sense of PSST, multi-quanton W-state can be visualized with analogy to a Möbius strip, in which one side (track A) holds the even-order permutations of the reference state and the other (track B) holds the odd-order permutations (negated for fermions). Under rotation through 2π, track A morphs to track B, and vice versa. Because addition is commutative, the rotated and original states are exactly identical.

It is noteworthy that the concept of even- and odd-order permutations is necessary to make sense of the sign flip for a single isolated fermion rotated through 2π. The even- and odd-order permutations are mutually distinct physically, even if other quantons are nowhere in the physical vicinity.

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[25] For this reason, whether PSST can be considered a *theorem* (*i.e.*, a deduction about how nature *must* work) is questionable.

2.5.4 Fermion Exclusion

The anti-symmetric form of fermion W-state in Eq. 26 has an extremely important implication. If the translational and rotational W-states of any two quantons coincide exactly at some point, the entire multi-quanton state, vanishes at the point, in effect excluding all fermions from the region. If the translational states coincide, the cancellation is avoided only if the two have opposite spin alignments. This is the well-known Pauli Exclusion Principle.

3 Q-2: Physics of Quantum Measurement

What has been presented thus far represents the full extent of the theoretical development of W-state, *as a stand-alone wave theory.* It is henceforth referred to as Q-1. Attention now turns to measurement processes, which have been steadfastly ignored until now.

No quantum theory of wave propagation by itself can explain wave-particle duality or the mechanics of wavefunction collapse. That is as true of Q-1 as of standard quantum theory and the alternatives.

3.1 Qualitative Nature and Implications of Quantum Measurement

What kind of physics might underlie measurement processes and explain why they are so different from interactions that drive Q-1 dynamics? One clue lurks within Q-1 itself. It is apparent that Q-1, in its own terms, does not account comprehensively for all possible types of interactions between a quanton and its surroundings.

3.1.1 Non-conservative Interactions

A noteworthy limitation of Q-1, both in the new framework and in conventional quantum theory, is that it can only accommodate conservative forces. To predict phase-sensitive interference effects, it relies on action integrals (Eq. 17), which require well-defined Lagrangian functions. It is well-known from classical mechanics, however, that not all force laws are amenable to Lagrangian[26] formulation. The simplest example is viscous damping, *viz.*,

$$F = -b\dot{x} \tag{28}$$

There is no Lagrangian function that satisfies Eqs. 10-12 and Eq. 28. It follows that the scope of Q-1 is sharply limited. Either it must be posited that non-conservative forces do not exist at all in the quantum realm, or Q-1 is utterly unable to explain how a quanton would respond amidst non-conservative interactions with the surrounding environment. Furthermore, insofar as Q-1 claims to be a universal theory, it is unable to encompass non-conservative forces in the macroscopic realm.

The upshot is that nature in the microscopic realm features two qualitatively different forms of interactions between quantons and their surroundings. By all appearances and evidence, it is a dichotomy of fundamental nature. In fact, non-conservative interactions are so jarring - literally and figuratively - that their effects on the quanton *cannot be quantified by a force law*[27]. They require theoretical treatment radically dissimilar from Q-1.

3.1.2 Wave-Particle Duality

In the quantum realm, measurement processes are enigmatic in several key respects. One is that wavefunction collapse implies a form of dynamic evolution (Rule 2) that could not be more different from that of the Schrödinger equation (Rule 1). In the two-slit[28] experiment, the W-state of the electron, which fans out widely during transit through the apparatus, abruptly narrows by many orders of magnitude upon contact with the detection screen. In the EPR experiment, photons whose dynamic attributes are indefinite during their journeys register definite polarizations when they encounter the detectors. In both scenarios, the measurement act results in discontinuation of the wave-like W-state evolution that had previously been taking place. Q-1 dynamics cease to apply, and radically different dynamics law takes over. This makes it extremely hard to unite and harmonize the two dynamics under a single formalism.

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[26] Neither therefore are they amenable to Hamiltonian or Hamilton-Jacobi formulation.

[27] In the quantum realm, it is not correct to speak of non-conservative *forces.* The word *interaction* must be be used instead.

[28] The one-slit and two-slit experiments make the point equally well, as both feature diffraction and interference effects.

Particles and fields coexist in classical physics, but only as distinct separate entities that themselves are entirely one or the other. Quantum theory, on the other hand, must explain how wave- and particle-like ontologies can coexist within one type of entity.

The quantum theory of measurement is a theory of discontinuity. Measurement events result in discontinuous change in W-state across the rest manifolds of quantons. The quanton ontology is always primarily wave-like, although the spatial width of the W-state has great dynamic range. The quanton is a particle in that the spatiotemporal distributions of W-state on the two sides of the rest manifold are jointly subject to *global conservation constraints.*

3.1.3 Wavefunction Collapse

Wavefunction collapse implies a dramatic narrowing of the spatial extent of the W-state resulting from a measurement event. The post-measurement width, however, cannot be literally zero, as that would violate the uncertainty principle; the post-measurement W-state must form a valid wave packet. This incidentally draws attention to a blatant contradiction - or lack of linguistic clarity - that is commonplace in mainstream discourse, but is seldom acknowledged or explained. The uncertainty principle implies that the spatial width, Δx, of a quanton cannot be pinched down to the Compton wavelength ($\hbar/mc$), let alone zero, without causing the quanton to flit away at the speed of light, yet compressing Δx to zero is exactly what is alleged to happen in wavefunction collapse, when the quanton is said to be detected *at* a definite position.

3.1.4 Chance and Hidden Variables

A second enigmatic feature is that the post-measurement W-state is related to the pre-measurement state only statistically through the Born Rule. Given the pre-measurement W-state, only the probability distribution characterizing the post-measurement W-state can be predicted. There are only two types of logical explanation: (*i*) chance, and (*ii*) hidden variables.

Chance, in this context, essentially signifies a local act of dice rolling at the measurement site. That is congruous with the notion that the W-state is genuinely indeterminate up until the measurement event. However, it cannot possibly be the whole story - certainly not when measurement processes are distributed in space-time, as is necessarily always the case because the pre-measurement W-state is spread out[29].

The term *hidden variables*, which goes by the term *P-state* in the new framework of Q-2, signifies embedded elements of reality that pre-determine or constrain measurement outcomes. They are carried passively by the W-state and have no effect on the dynamic evolution of the W-state until the measurement event.

Under the local causality strictures of classical physics, severe conditions are imposed on the hidden variables. In the two-slit experiment, one thread must be uniquely special in carrying "positive" P-state; a positive detection event registers at the point where that thread intersects the screen, whereas all other threads terminate at the screen without a detection. In the EPR experiment, local hidden variables means a playbook of instructions that prescribes for each photon a pre-determined outcome for any conceivable type of measurement to which it could be subjected.

3.1.5 EPR Experiment

The Einstein-Podolsky-Rosen (EPR) experiment is reviewed not only because of historical significance, but also because it is the simplest archetypal experiment that exposes the startling implications of distributed measurement processes. It principally signifies the two-photon experiments conducted by Clauser and Aspect, although the original 1935 paper was couched in terms of particle momenta rather than photon polarizations.

Two mutually entangled photons, jointly emitted from an atomic source, travel in opposite directions before encountering polarization detectors. The measurement outcome for each photon is binary: it is either passed or blocked by the polarization filter.

The P-state of each photon can be thought of as a function that outputs 0 (blocked) or 1 (passed) as a function of the azimuthal angle, θ, at which the filter is oriented relative to some reference angle in the laboratory. It can be visualized as circular disk (clock face), marked 0 in the first (12:00 to 3:00) and third (6:00 to 9:00) quadrants

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[29] From the uncertainty principle, it follows that the post-measurement W-state is also spread out, albeit by much less.

and 1 in the other two. The outcome is determined by which pair of opposite quadrants the polarization axis of the detector intersects.

The local hidden variables theory offers the following explanation of EPR: At the atomic source, a clock face is created and oriented at some random angle relative to the laboratory reference axis. Each photon takes with it a copy of the clock face. The outcome for each photon depends only on its own P-state and the orientation angle, θ, of the filter that it encounters.

The theory correctly predicts three experimental facts:

- If an ensemble of outcomes at either detection site is observed in isolation, 50% of photons are passed and 50% are blocked, irrespective of the orientation angle of the detector at that site.
- If the polarization axes of the two filters are aligned, it is always the case, for each photon pair, that either both are passed or both are blocked.
- If the polarization axes of the two filters are perpendicular to one another, it is always the case, for each photon pair, that one is passed and the other is blocked.

3.1.6 Bell's Theorem

Bell proved, through simple mathematical argumentation, that any local hidden variables of theory of the kind just described is limited in how strongly outcomes at multiple measurement sites can be correlated statistically. The sites are assumed to be space-like separated; it therefore follows from classical causality that the P-state of either photon during transit is fixed; it cannot be affected by any measurement process to which the other is subjected or the outcome of that remote measurement event. The limited correlation strengths arise fundamentally because the single-photon P-states bear the heavy burden of pre-determining outcomes for all possible detector configurations. In the EPR setting, that means that the filter angle, θ, of each detector acts, in effect, as a free variable that can be chosen at will[30] by the experimenter.

Bell's theorem imposes quantitative, experimentally testable limits on the correlation strengths at θ values intermediate between 0 and $\pi/2$. Suppose that both polarizers are initially aligned vertically (as a baseline case) and that polarizer A is rotated clockwise by angle α. This has the effect of diminishing the correlation, causing some pairs of photons to yield mismatches. Under the assumption of locality, the mismatches arise entirely from the change in A's alignment relative to the incident photon.

Suppose next that polarizer B is rotated counter-clockwise by angle α. The further diminution of the correlation is wholly attributable to B's changed alignment. In the resulting ensemble of results, any mismatch, under the assumption of locality, is attributable to the departure of either A's or to B's alignment from the vertical. In some cases, both photon results differ from what would have been obtained with both polarizers vertically aligned, resulting in a match. It follows that the mismatch rate, n, when the polarization angle difference is 2α can be no greater than twice the mismatch rate at α. More generally:

$$n(\theta_1 + \theta_2) \leq n(\theta_1) + n(\theta_2) \tag{29}$$

The result in Eq. 29 is *Bell's inequality.* Quantum theory, for a pair of photons mutually entangled in the singlet state, predicts a mismatch rate of

$$n(\theta) = \sin^2 \theta \tag{30}$$

which violates the Bell inequality. The experimental results of Clauser, Aspect, and Zeilinger conclusively demonstrate that the Bell limits are indeed violated and that the predictions of quantum theory are vindicated.

The upshot is that no local hidden variables theory can possibly explain the quantum facts. No viable formulation of quantum theory can exist within the strictures of locality causality assumed and formalized in classical physics[31]. Bell and the experiments together *proved* that the quantum realm is non-local.

3.2 Non-Locality

The implications of Bell's theorem, in conjunctions with the experimentally verified quantum facts, are so profoundly startling that they necessitate nothing less than a wholesale departure from the premise of local causality.

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[30] Super-determinism is ruled out as a logically tenable explanation.

[31] Including classical electromagnetism, general relativity, and even Q-1 as a stand-alone wave theory.

3.2.1 Strong Non-Locality

We begin our foray into non-locality in the setting of Galilean relativity, *i.e.*, special relativity in the limit of $c \to \infty$. Time becomes absolute and decoupled from space.

In the space-time structure of Galilean relativity, it is perfectly tenable to have blatantly non-local forms of physical law, in which the local physical state at point $\underline{x}$, at time $t = 0^+$ (*i.e.*, infinitesimally downstream of $t = 0$), depends on the state at *any other point in space* at time $t = 0^-$, no matter how spatially distant from $\underline{x}$. This is *strong non-locality.* It countenances lateral time travel, but not backwards time travel (which would be vitiated by circular causation logic).

Non-locality is not so easily compatible with the space-time structure of special relativity, for two reasons. First, non-local physical law relies fundamentally on the existence of absolute manifolds, which exist in the space-time structure of Galilean relativity (as constant-time 3D manifolds) but not that of special relativity. Secondly, special relativity, in its strong form, explicitly prohibits superluminal signaling. Quantons, however, are material entities whose rest manifolds are absolute. In principle, it is logically tenable to have strongly non-local physical law within quantons, much like in Galilean relativity. That would be compatible with the weak, but not the strong, form of special relativity.

3.2.2 Weak Non-Locality

The types of non-local effects, such as Bell inequality violations, that actually crop up in the quantum realm and have been witnessed experimentally are more subtle than non-locality of the blatant kind. They exemplify *weak non-locality*, which is compatible with the strong form of special relativity.

Consider the scenario of a quanton, for which Q-1 physical law reigns exclusively everywhere except on a single rest manifold, $\mathcal{M}$. At some or all points on $\mathcal{M}$, the quanton encounters a detector, which is distributed in space-time just like the quanton itself. At each point on $\mathcal{M}$ at which a detector element is encountered, packets are broadcasted and received at other points on $\mathcal{M}$, much like on the constant-time manifold in Galilean relativity. The packets can be thought of, metaphorically, as distress signals that reverberate throughout the quanton internally.

The lateral (space-like) transfers of packets on $\mathcal{M}$ are all that it takes to realize strong non-locality within quantum (or classical) systems. To prevent superluminal signaling[32], however, imposes strict information-theoretic conditions on the packets and the physical laws governing what happens during measurement events.

3.2.3 Absolute Randomness

The first information-theoretic implication of weak non-locality is that the information *content* of the packets must be purely stochastic. Otherwise, a packet could convey information about local conditions at the point on $\mathcal{M}$ from which it originates. It follows that weak non-locality logically requires *absolute randomness.*

3.2.4 Dynamic Implications of Weak Non-Locality

The preclusion of superluminal signaling imposes two additional information-theoretic criteria:

- No intervention[33] at any point on $\mathcal{M}$ can exert controllable influence on the W-state evolution at other points on the manifold.
- From (notionally passive) observation of the W-state evolution at some point on $\mathcal{M}$, nothing can be inferred about local conditions elsewhere on the manifold.

From these criteria, it follows that weak non-locality shapes the fundamental nature of quantum state and the properties of physical law that governs its evolution amidst measurement processes.

3.3 Determinate Model of Quantum Jumps

This section presents a complete mechanistic description, in terms of the deep quantum reality of W-state and P-state in the new framework, of a *quantum jump*, which signifies the most familiar and best "understood" type of measurement process in conventional quantum theory.

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[32] *Signaling*, in special relativity, means the conveyance of *information* in the strong sense, *i.e.*, in contradistinction to noise.

[33] Intervention signifies contrived manipulation of a quantum system through a measurement-like interaction.

3.3.1 Simplified Model of Pure Measurement Processes

In a *pure measurement process*, a quanton experiences a non-conservative interaction with the environment, which is confined entirely to a rest manifold, $\mathcal{M}$, of the pre-measurement W-state, denoted as W^-. The interaction precipitates a global exchange of information on $\mathcal{M}$, in fashion consistent with the strictures of weak non-locality. The final result is a post-measurement state, W^+, that differs discontinuously from W^- at all points on $\mathcal{M}$.

The interaction is non-conservative in that it cannot be quantified in terms of a Newtonian force law derivable from a Lagrangian function. Instead, it is represented abstractly as $U(\underrightarrow{x})$, which denotes the interaction with the environment locally at point $\underrightarrow{x}$ on $\mathcal{M}$. The quantitative character of U is left vague, but is important in two respects.

3.3.2 Measurement Event Totality

Derivable from U is a measure of the *totality* of the local measurement event that takes place at $\underrightarrow{x}$. It can be thought of as a fuzzy truth value on a continuum from 0 to 1, wherein 1 represents a "total" measurement event, in which the W^- threads are completely destroyed and replaced wholesale by all-new W^+ threads. A totality value of 0 represents the absence of any disruptive local interaction with the environment, in which case the local W-state continues on undisturbed. Intermediate values result in partial measurement events, in which the amplitudes of the W^- threads are scaled down by the totality factor and new W^+ threads are created to a complementarily proportionate degree.

From the application of a single totality factor uniformly to all threads at any measurement site, it follows that momentum is locally conserved, and that $\mathcal{M}$ is therefore a rest manifold of both W^- and W^+. The notion of quanton proper time remains intact, despite the global metamorphosis of the W-state.

3.3.3 Measurement Outcome Probabilities

Viewed as a spatio-temporal function defined on $\mathcal{M}$, U represents a distributed measurement process. Its global quantitative character indicates the *type* of measurement process to which the quanton is subjected. That translates to a Hermitean operator, A, on the Hilbert space to which W^-, as a square-integrable function on $\mathcal{M}$, belongs. W^+ is an eigenvector of A. The probability of its being in the eigenspace corresponding to given eigenvalue a is

$$P(a) = \left\langle W^- \right| \mathbb{P}_a \left| W^- \right\rangle \tag{31}$$

in which $\mathbb{P}_a$ is the projection operator onto the eigenspace of a.

The notion of pure measurement processes is a simplifying abstraction that isolates the conditions under which a quantum jump from W^- to W^+, describable in terms familiar from conventional quantum theory, takes place. Interactions distributed over multiple rest manifolds are considered a sequence of pure measurement processes.

3.3.4 Determinateness

Since the time of Bohr's early work on atomic structure, the term *quantum jump* has been shrouded in mystique, vagueness, and controversy because it has not answered the basic story-telling questions of what, where, when, and how. The new framework makes a major step toward solving the measurement problem by supplying answers.

The new framework maintains that prior to the measurement event, W^- is an objectively real state of indefiniteness[34]. The measurement outcome is decided at the instant of measurement by acts of dice rolling that take place at all points on $\mathcal{M}$ at which $|\psi|^2$ is non-zero. Global information exchange on $\mathcal{M}$, permitted within the strictures of weak non-locality, yields a measurement outcome (*i.e.*, selection of an eigenvalue, a, and corresponding eigenvector) as an aggregated result derived from the distributed dice rolling.

The pre- and post-measurement W-states, the intervening acts of dice rolling on $\mathcal{M}$, and the ensuing exchange of information that transpires on $\mathcal{M}$ together furnish a complete list of the constituents of deep quantum reality underlying the simplest types of measurement processes.

The new framework agrees with standard quantum theory on the facts and phenomenology, but it additionally provides a detailed picture of an underlying deep reality. In that respect, it can be said to be a *determinate* theory[35]. The preceding account of simple measurement processes is much like von Neumann's original postulate

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[34] Unless it is already in an eigenstate of the measurement operator, A.

[35] Determinateness, quite obviously, is altogether different in meaning from determinism.

of wavefunction collapse, but fills in the story detail. In particular, the tale of thread destruction and creation takes a stance on the infinite regress issue.

3.3.5 Measurement Outcome Correlations

Under weak non-locality, it is possible to realize, within single quantons or systems of mutually entangled quantons, strong measurement outcome correlations that cannot be explained by any local hidden variables theory. A mechanistic model of how global information exchange and coordinated response on $\mathcal{M}$ can produce strong correlations is proposed in this section.

We consider the scenario of a quanton, for which Q-1 physical law reigns exclusively everywhere except on a single rest manifold, $\mathcal{M}$. In this simplified scenario, the P-state at each point on $\mathcal{M}$ contains only packets originating from other points on $\mathcal{M}$.

Suppose that there are finitely many (N) measurement sites on $\mathcal{M}$, whereat the quanton locally encounters detector elements. For simplicity, assume univariate local measurement outcome spaces at each site, meaning that the measurement outcome (W_n^+) at the n'th site is mappable to a single number, μ_n.

The measurement outcomes collectively conform to a statistical distribution represented by an N-dimensional PDF, *viz.*,

$$P(\mu_1, \mu_2, \ldots, \mu_N) \tag{32}$$

which is normalized:

$$\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} P(\mu_1', \mu_2', \ldots, \mu_N')\, d\mu_N' \cdots d\mu_2'\, d\mu_1' = 1 \tag{33}$$

All statistical properties (ensemble averages) of the measurement outcomes are derivable from the PDF. Ensemble instances differ only in particular random values in the packets generated at the sites. The functional form of P in Eq. 32 depends on the local conditions (W^- and U) at the sites and is derivable from Eq. 31.

In a local hidden variables theory, the PDF decouples, *viz.*,

$$P(\mu_1, \mu_2, \ldots, \mu_N) = P(\mu_1)P(\mu_2) \cdots P(\mu_N) \tag{34}$$

That the PDF, in general, does not decouple reflects the particle-like wholeness of quantons, which measurement processes conserve.

3.3.6 Decentralized Innovation and Arbitration

The purpose of the mechanistic model is to demonstrate, from a purely information-theoretic standpoint, how strong measurement outcome correlations can be realized within the strictures on weak non-locality. The objective is to explain (i) what has to happen in individual systems to produce outcomes that conform to the ensemble PDF, and (ii) how those requirements can be met and implemented.

For the purpose of describing the mechanism, the local presence of the quanton, at each measurement site, is portrayed in fictional terms of a computing agent. A story will be told of how the agents operate in decentralized fashion, but use information globally exchanged with one another on $\mathcal{M}$ and cooperate to produce measurement outcomes that conform statistically to P.

The story synoposis is as follows:

- When the quanton locally encounters a detector element, the computing agent at the measurement site generates a packet with purely random information content. It broadcasts the packet on $\mathcal{M}$.
- Global information exchange transpires on $\mathcal{M}$. Each agent receives packets from all others.
- Each agent has knowledge of P, which can be regarded as a table published globally on $\mathcal{M}$. Each agent consults the table, in conjunction with its own innovation and that of the others, to generate its own local measurement outcome (μ).

3.3.7 Innovation Components

In the mechanistic model, the packet innovations are means to the end of generating the measurement outcomes. Conceptually, this is no different from what a conventional computer does to generate a normally distributed random number (x) from a random number (r) uniformly distributed on the unit interval. It solves for x such that the definite integral under the Gaussian curve to the left of x equals r.

To generalize the procedure to a multivariate PDF of N dimensions, one requires N uniformly distributed numbers ($r_1, \ldots, r_N$), along with a specified order in which the dimensions will be indexed. In the first step, x_1 is computed such that the N-dimensional hypervolume to the left of x equals r_1. In the second step, x_2 is computed based on the ($N-1$)-dimensional hypervolume corresponding to the PDF slice conditioned on x_1. And so forth.

To implement the procedure in a decentralized setting, the agents must agree upon a prioritization of the measurement sites. The process through which agreement is forged is called *gambit arbitration.* It is simple to implement. Each agent generates an innovation component called a *gambit*, which is a random number uniformly distributed on the unit interval. From the global information exchange on $\mathcal{M}$, each agent ascertains its rank in the lineup by comparing its own gambit to those of the other agents[36].

The aforementioned $r_1, \ldots, r_N$ are each generated separately by the agents. It therefore suffices for each packet to contain two random numbers: gambit (γ) and index (r).

3.3.8 Measurement Outcome Computation

After gambit arbitration, the agents perform a sequence of definite integral evaluations to derive the measurement outcomes:

- The highest-ranking thread selects μ_1, *viz.*,

$$\int_{-\infty}^{\mu_1}\int_{-\infty}^{\infty}\cdots\int_{-\infty}^{\infty} P(\mu_1', \mu_2', \ldots, \mu_N')\, d\mu_N' \cdots d\mu_2'\, d\mu_1' = r_1 \tag{35}$$

- The second highest-ranking thread selects μ_2, *viz.*,

$$\int_{-\infty}^{\mu_2}\int_{-\infty}^{\infty}\cdots\int_{-\infty}^{\infty} P(\mu_1, \mu_2', \ldots, \mu_N')\, d\mu_N' \cdots d\mu_3'\, d\mu_2' = r_2 \tag{36}$$

  in which μ_1 is the value selected in the first step.

- The third highest-ranking thread selects μ_3, *viz.*,

$$\int_{-\infty}^{\mu_3}\int_{-\infty}^{\infty}\cdots\int_{-\infty}^{\infty} P(\mu_1, \mu_2, \mu_3', \ldots, \mu_N')\, d\mu_N' \cdots\, d\mu_3' = r_3 \tag{37}$$

- ...

- The lowest-ranking thread selects μ_N, *viz.*,

$$\int_{-\infty}^{\mu_N} P(\mu_1, \ldots, \mu_{N-1}, \mu_N')\, d\mu_N' = r_N \tag{38}$$

3.3.9 Natural Computation

The mechanistic model has now been described in full. It is an outline of *how* nature, in principle from a purely information-theoretic standpoint, can operate within the strictures on weak non-locality to produce measurement outcomes in individual systems that conform statistically to a specified arbitrary PDF.

Natural computation is a metaphor for what nature has to do to make it happen, obviously without human computing technology. Eqs. 35-38 underlie the Born Rule and Bell inequality violations.

The narration of the mechanistic model posits multiple computing agents because we naturally think of space as a barrier separating them. In natural computation, however, space does not act as a barrier.

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[36] Gambit arbitration is conceptually no different from what CSMA/CD does to mitigate network traffic collisions.

3.4 Entanglement Analysis and P-state

3.4.1 Entangled Quanton Pairs - Double Measurements

In the EPR experiment, it is always the case that one photon registers with polarization up and the other registers polarization down[37]. The experiment is an application of the preceding analysis for $N = 2$ measurement sites.

In the double measurement scenario, the photons each encounter detectors in their respective paths. The detection events are space-like separated. Upon encountering its detector, each photon[38] generates a gambit-index pair. The photon drawing the highest gambit gets first crack to choose whether it registers polarization up or polarization down. The other photon is then constrained to produce the opposite polarization.

3.4.2 Entangled Quanton Pairs - Single Measurements

Suppose that just one photon (A) encounters a detector, while the other (B) continues on and is not subjected to measurement until a later time.

On the rest manifold ($\mathcal{M}$) intersecting the first detection site, only A generates a packet. The gambit (γ) in that packet prevails by default. The index value (r) in the packet determines whether A registers polarization up or polarization down.

Either way, B acquires an *entanglement obligation* to produce the opposite polarization when it is eventually measured. To account for the obligation, the state of B must change discontinuously on $\mathcal{M}$. It is not the W-state, but a supplemental form of local quantum state (P-state), that changes.

This is actually the scenario that more generally represents the dual detection experiments, since the detections almost never occur exactly simultaneously (*i.e.*, with one rest manifold intersecting the measurement events at both sites). P-state ensures that the deferred measurement outcome for B is the same as it would have been had the detections been simultaneous.

P-state signifies non-local hidden variables that keep track of and enforce entanglement obligations. It implements spooky action at a distance in the sense expressed by Einstein; the state of B really does change as a result of an act of observation[39] by the detector at A. Observation creates (but does not *control*) reality in that it affects post-measurement W-state creation and evolution, both locally and remotely.

3.4.3 Wavefunction Collapse - Full Detection

The EPR analyses apply to the fates of threads in the two-slit experiment. As an electron transits through the apparatus, its threads fan out spatially. In a full detection scenario, the quanton encounters a wide detector that completely intercepts the fan-out area. The measurement event totality everywhere on $\mathcal{M}$ is 1. It is then always the case that only threads in a tightly concentrated area on the detection screen register a positive detection event, whilst threads elsewhere register negative. Wavefunction collapse is effected, and the quanton appears at only one measurement site as a concentrated[40] particle.

What becomes of the W-state at the positive and negative detection sites? At the negative detection sites, the W-state is destroyed, and no new threads are created. The surroundings remain unaware of the pre-measurement presence of the quanton. In the close vicinity of the positive detection site, new thread creation greatly intensifies the W-state; the intensification becomes manifest to the surroundings. It follows that W-state dynamics, amidst measurement events, are globally, but not locally, conservative of particle count.

3.4.4 Wavefunction Collapse - Partial Detection

In a partial detection scenario, the quanton encounters a narrower detector that only partially intercepts the fan-out area. The measurement event totality is 1 at some points on $\mathcal{M}$ but 0 everywhere else. There are then two possible outcomes. One is that a positive detection occurs. As in the full detection scenario, the W-state intensifies at the positive detection site but vanishes everywhere else on the detector surface. The W-state of threads not

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[37] This is the Aspect experiment for the case of aligned polarization axes in the detectors ($\theta = 0$).

[38] More correctly, the natural computing agent representing the entangled photon pair at the measurement site.

[39] In the quantum realm, observation is active in that is the source of environmental intervention (U) at the measurement site.

[40] Not exactly a *point* particle, but of a size several orders of magnitude smaller then the pre-measurement wavefunction spread.

intercepted by the detector continue on undisturbed, but they effectively become neutered by the P-state. The P-state guarantees that they will never register positive; they become *ghost waves.*

The other outcome is that no detection occurs. This is known as a Renninger negative-result event [6], wherein the W-state vanishes at all points on the detector surface. The W-state of threads not intercepted by the detector continue on undisturbed, but the P-state renders them more potent. When the surviving W-state eventually encounters a full detector, a positive detection is certain to occur.

In both cases, the discontinuous change in P-state on the surviving threads has a strengthening or weakening effect, not on the W-state directly but on the forecasting odds of positive detection when the surviving W-state is eventually subjected to measurement. In this way, P-state absorbs quantum Bayesianism (QBism) into the new framework as an epistemic tool.

3.4.5 Impact of P-state on Measurement Event Dynamics

The post-measurement W-state, on a rest manifold on which the quanton encounters a non-conservative interaction with the environment, is governed by a non-local dynamics law of the general form:

$$W^+ = f(W^-, U, \nu, P^-) \tag{39}$$

in which the quantities all denote spatio-temporal distributions on $\mathcal{M}$. ν denotes the random content (gambit and index) of packets generated as a result of non-zero U.

P^- denotes the pre-measurement P-state, which can be thought of as a bagful of packets that originated on other threads. The packets are notionally sealed in that they have been carried passively by the threads and have not yet had any bearing on the W-state evolution.

In the absence of any local measurement activity at point $\underset{\rightarrow}{x}$ on $\mathcal{M}$, $U(\underset{\rightarrow}{x})$ is notionally zero, and the functional form of f in Eq. 39 becomes a delta function depending only on $W^-(\underset{\rightarrow}{x})$, signifying deterministic evolution of the W-state locally under conservative forces.

3.4.6 Statistical Form of Measurement Event Dynamics

Consider an ensemble averaging[41] over the dependence on ν and P^- on the right-hand side of Eq. 39. This yields a probability density function (PDF) for W^+, *viz.*,

$$\mathcal{P} = \mathcal{F}(W^-, U) \tag{40}$$

Eq. 40 is essentially the Born Rule (Eq. 31), which yields the statistical dependence of the non-deterministic W-state evolution on the pre-measurement W-state (W^-) and the intervention (U).

Consider next the fictional scenario of the approximating local hidden variables theory, wherein the dependence on P^- in Eq. 39 is suppressed. Ensemble averaging over only the ν-dependence then yields a modified form of Eq. 40, *viz.*,

$$\mathcal{P}_L = \mathcal{F}_L(W^-, U) \tag{41}$$

Weak non-locality requires that Eqs. 40 and Eq. 41 coincide exactly, *viz.*,

$$\mathcal{F}_L = \mathcal{F} \tag{42}$$

Eq. 42 states that the statistical relationship between W^- and W^+, for a single quanton manipulated and observed in isolation, is unaffected by the fates of other quantons with which it is entangled. The dependence on P^- in Eq. 39 is relevant only in accounting for correlations with the fates of those other quantons.

3.4.7 P-state Commingling Between Measurement Events

Q-2 posits that quantons become entangled with one another if their W-states interact or become spatially interwoven significantly at any time between measurement events. Their rest manifolds become conjoined, and their P-states become commingled and evolve in tandem. Entanglement can arise owing to common genesis (*e.g.*, the

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[41] Because of absolute randomness, quantum ensemble averages, unlike in classical statistical mechanics, have absolute significance.

photon pairs in the Aspect experiment) or coming into contact (*e.g.*, two electrons that were originally separate, but each allowed to diffuse into a box enclosure). Once entangled, the quantons remain entangled until the next measurement event, even if they become spatially separated and cease to interact. In this respect, P-state dynamics, unlike W-state dynamics, are irreversible.

After measurement events, entanglements with the past are broken, and W^+ begins anew with fresh P-state. Entanglements that bear on the next measurement event are either "congenital" (*e.g.*, EPR photon pairs emitted at the atomic source) or acquired through W-state contact with other quantons.

3.4.8 Information-Theoretic View of Quantum State

The preclusion of superluminal signaling applies only to W-state. Lateral exchange of P-state, by contrast, is permitted. It follows that weak non-locality logically implies two types of quantum state that are fundamentally different in their information-theoretic stature. Interaction between quantons and their surroundings involve only exchange of W-state information, whereas P-state information is strictly internal to quantons. P-state is thus a truly hidden variable.

3.5 Difficulty of the Measurement Problem

It is thoroughly well-appreciated that the measurement problem is one of the most conceptually intractable issues at the heart of quantum foundations and the one that has most thwarted progress. What is it about the measurement problem that is so stubbornly intractable? Why cannot measurement events be clearly identified as objectively real physical processes and described in ordinary physics terms?

3.5.1 Tension between Quantum Theory and Relativity

The distributed nature of quantum measurement processes cannot be squared easily with the strictures of special relativity. Although Bell's insight, buttressed by the experimental evidence, conclusively rules out local hidden variables, issues of non-locality were readily apparent from the outset in wavefunction collapse[42] and wave-particle duality. What has been developed of Q-2 thus far offers a solution to this aspect of the measurement problem, but the tension between quantum theory and special relativity is much broader in scope and encompasses a multifaceted host of issues.

One symptom of the tension is the pedagogical approach to quantum mechanics. Conventional introductions focus exclusively on the non-relativistic theory[43] and defer the relativization (*i.e.*, quantum field theory and electrodynamics) to advanced courses. Why is the quantum physics curriculum not relativistic though-and-through from the outset? Historically, there have been at least two reasons, beyond what has already been noted, for the diffidence.

The conventional wisdom has held that interplay between the uncertainty principle and $E = mc^2$ makes relativistic quantum theory untenable as a single-particle theory and inseparable from quantum field theory. The new framework rejects that argumentation. There is nothing inherent in the structure of Q-1 that logically requires proliferation of degrees of freedom (*e.g.*, creation of virtual particles) within a quanton when $c < \infty$.

The second reason pertains to the Dirac equation. It is the mathematical core of W-state dynamics, but historically, the equation has been greatly overinterpreted. It is conventionally construed as implying that spin is a logical consequence of the fusion of quantum theory and relativity. The new framework also rejects that contention. The equation readily accommodates and meshes well with spin, but it does not follow that it *predicts* spin. It is perfectly feasible, within Q-1, to have a Dirac-style solution for the hydrogen atom with a spinless electron; the only difference would be the absence of spin-orbit coupling. Furthermore, the notion of spin as following from relativity fails to explain spin ontology in non-relativistic settings.

It is likewise a questionable contention that the Dirac equation *predicts* the existence of anti-matter. On the one hand, it is claimed, first by Dirac himself, that the world is pervaded by a fully occupied negative-energy sea[44], which, in conjunction with the exclusion principle, explains the existence of positive-energy solutions. On the other hand, the equation itself offers no explanatory insight into the asymmetry of matter and anti-matter

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[42] The non-locality of wavefunction collapse was the first thought experiment challenge that Einstein posed at Solvay in 1927.

[43] Odd, considering that many students have mastered special relativity at this stage of their education.

[44] This is one of the first examples in which quantum physics strayed into unwarranted fiction and fantasy.

abundances. Nor does the Dirac theory of the electron and positron leave any clues as to why attempts to replicate its predictive success have not borne fruit. Is it any more airtight or unimpeachable in its predictive reasoning than the failed (or at least, unvindicated) models that predicted supersymmetric particle pairings?

3.5.2 Tension between Rule 1 and Rule 2

From the outset, quantum mechanics has been troubled by the challenge of explaining the coexistence of opposites: (*i*) Rule 1 and Rule 2 dynamics and phenomenology, and (*ii*) wave- and particle-like ontology in a single physical entity. Its split character and landscape is unlike the unifications of electricity and magnetism, of electromagnetism and optics, of space and time, and of space-time and gravitation that became the capstones of the classical physics tradition.

Generally speaking, Rule 1 (Q-1) has had the upper hand and been favored because it is a classical *kind* of theory that can be regarded as stand-alone. It is a theory of continuous deterministic dynamic evolution of a wave-like entity that fills 4D space-time. It is in keeping with the causal structure of classical physics, aside from the type of non-locality exposed by the AB effect.

Whereas Rule 1 has a well-developed mathematical formulation and a single well-established governing equation, Rule 2 has never been more than an *ad hoc* insertion that does not mesh naturally with the rest of the theory. It is a theory about discontinuation of the unitary evolution of the W-state under Rule 1. Its only mathematical substance is the Born Rule and projection operators onto eigenspaces. It has no dynamics of its own that are recognized within the conventional formalism.

3.5.3 Infinite Regress

There has long been deep-seated unease with the notion of wavefunction collapse and reluctance to take an affirmative stance on it. Von Neumann posited wavefunction collapse as an *ad hoc* postulate because the issue of infinite regress could not be resolved in any satisfactory manner congruous with the Rule 1 formalism. *Infinite regress* is the logical consequence of ambivalence about whether a measurement event, which breaks unitary evolution of the W-state, actually occurs. The alternative hypothesis is that the wavefunctions of observer and observed system become entangled[45] and continue to evolve unitarily.

The question of whether unitary evolution discontinues is not trivial. As a simple example, consider the splitting of a photon beam, followed by interception of the daughter beams at detection devices. Although the insertion of the beam splitter, at first glance, seems like a disruptive intervention, the beam-splitting itself definitely does not count as a measurement process, since the daughter beams can be recombined without loss of the original phase relationships or beam directionality. Absorption of the photons by phosphorus atoms in the detection devices seems like a more plausible candidate to be considered a measurement process, but even that cannot easily be affirmed[46] definitively, since photons subsequently emitted by the atoms might exhibit interference phenomena, erasing “which path” information. In then necessarily follows, in retrospect, that the photons could not have encountered any measurement obstructions during their journeys through the apparatus.

3.5.4 Copenhagen View of Measurement

From the outset, quantum theory - and not just the Copenhagen orthodoxy - has been notoriously inconclusive and noncommittal in saying what measurement *is* and means. Infinite regress underscores one aspect of the difficulty of the measurement problem.

Copenhagen takes a minimalist view as to what constitutes a measurement event[47]. It recognizes only forms of contrived intervention involving macroscopic instrumentation in well-defined experimental settings. Analysis of this type of scenario is aided by the simplifying assumption of the *Heisenberg cut*, which holds that the quantumness of the measurement apparatus can, for all practical purposes, be ignored since it is so much larger than the quantum system being investigated.

In effect, Copenhagen minimizes the measurement problem by restricting its scope and limiting discourse. This view of measurement serves well as a practical tool for predicting outcomes of experiments, but it cannot stand

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[45] In terms of Q-2, the P-states of the two systems become commingled and henceforth evolve in tandem.

[46] In this context, proving a positive (*i.e.*, that a measurement *has* occurred) is more difficult than proving a negative.

[47] In Copenhagen parlance, it is technically not correct even to speak of a measurement *event*, as that implies something well-localized.

as a general theory of nature. An obvious problem with it is that it leaves vague how quantum physics plays out in the natural world, removed from physics laboratories and physicists.

3.5.5 Consciousness as Measurement Trigger

Perhaps the narrowest and most extreme view holds that consciousness plays an essential role in what constitutes a definitive act of measurement. Taken seriously, it implies that quantum physics, as an all-encompassing theory of principle governing the universe, could not exist as such until intelligent life evolved into existence on Earth. That is true, but it is important to appreciate why the idea took root, historically first with von Neumann and Wigner, and has been durable and influential.

The human mind is the ultimate point of last resort where the buck stops. At that point, it seems quite clear beyond all doubt that a definite attribute value has been extracted from a quantum system. Somewhere along the way between the atom and the mind, a soup of potentia is converted into an actuality that is unmistakably definite, at least in the here-and-now universe.

Can a cat or mouse change the universe by looking at it? The new framework regards the retina as a hard backstop, and thus a source of non-zero U, to the impinging photon. It applies a disruptive force to a tiny area of the photonic wavefront, but that is enough to precipitate an information exchange that reverberates globally throughout the photon. In this respect, the observer initiates and indeed participates actively in the creation of new reality. Note, however, that there need be nothing complex or sophisticated about the observer as a physical system; it need not be coupled with any back-end intelligence. The photon could equally well be intercepted by an inanimate object.

3.6 Internally Triggered Measurement Events

A less trodden avenue of exploration is the conjectural notion of *internally triggered* “measurement” events, wherein the W-state of a quanton changes non-deterministically, but not because of any obvious interaction with surroundings. All of the types of measurement processes that have been described thus far - and the only types that standard quantum theory explicitly recognizes as such - are externally triggered in that they involve iteraction with a well-defined entity that acts as a measuring system extrinsic to the quanton. However, externally and internally triggered measurement events are indistinguishable in their impact on W- and P-state dynamics within the quanton.

3.6.1 Spontaneity in the Quantum Realm

Q-1, in combination with a restrictive view as to what qualifies as measurement events, yields a largely static picture of the microworld. It implies dynamic evolution that is deterministic almost everywhere almost all of the time, except when an observer willfully chooses to interrogate nature. That picture, however, cannot be accepted at face value. Not only does it intuitively not feel or smell right, it is well-known that the microworld is replete with instability and fluctuations. Simple examples include: (*i*) thermal cavity radiation, (*ii*) spontaneous emission from excited atomic electron states, (*iii*) radioactive decay of nuclei, (*iv*) tunneling phenomena, and (*v*) zitterbewegung fluctuations in atomic electron dynamics, including in ground states.

The concept of internally triggered measurement events, which can more simply be called *micro-measurements*, is meant to encompass such phenomena within Q-2, as a general theory of non-deterministic quantum processes.

A particularly instructive example of micro-measurement processes is Planck’s blackbody cavity, wherein photons are continually created and destroyed spontaneously - obviously without intervention on the part of any observer. Q-1 holds that the photonic W-states consist of two parts: (*i*) a 2D surface current density on the cavity wall, and (*ii*) an electromagnetic standing wave in the cavity interior arising from that current density source. Micro-measurements are random events, characterized by some temperature-dependent temporal probability distribution, that can originate anywhere on the cavity wall or in the interior. P-state coordination then causes a photon to be created or destroyed as a whole on a constant-time manifold in the rest frame of the cavity.

3.6.2 Schrödinger's Cat

Schrödinger's cat is an extreme implication of the noncommittal stance on what qualifies as a measurement event. It pertains to any quantum system whose untrammeled W-state evolution, under Q-1 dynamics alone, diverges into two or more dissimilar branches that become mutually incongruous.

The dissimilarity of the branches need not become manifest macroscopically; the riddle of the cat can arise purely within the microdomain. As a simple example, consider spontaneous emission. When can it be said that emission has occurred? When the photon is detected, according to the orthodox dispensation. But suppose that the photon is shunted away from the atomic source and into a cavity, where it is kept circulating perpetually and never "measured". Can it then be said that the emission never really occurred and the joint system of atom and photon remains perpetually in an entangled state of indefiniteness?

3.6.3 Decoherence

Decoherence represents a broad view toward measurement that is closely related to micro-measurements. In nature, quantum systems of all sizes are continually buffeted by interactions with their surroundings. Those interactions are fitful and disruptive, causing the W-state to lose its interesting quantum features (*i.e.*, interference effects) and preventing it from straying far from classical behavior. This view of measurement, unlike the preceding two, does not depend on the existence of physics laboratories or physicists.

Decoherence effects offer effective explanation of why quantumness is almost never manifest at macroscopic scales[48]. However, there is disagreement on the technical issue of whether the loss of coherence stems fundamentally from phase randomization or outright cessation of unitary evolution. Whereas prevailing thought on decoherence leans heavily toward phase randomization, Q-2 maintains that measurement events entail destruction and creation of threads.

3.6.4 Wavepacket Expansion or Random Walk?

A peculiar feature of stand-alone wave theory is that free quanton wavepackets are not stable[49]. A free quanton whose wavefunction is initially concentrated spreads out with the passage of time. For a Gaussian wave packet of width Δ_0 at initial time $t = 0$, the width at future time $t > 0$ is [17]:

$$\Delta(t) = \Delta_0 \left[1 + \left(\frac{\hbar t}{m \Delta_0^2} \right)^2 \right]^{1/2} \tag{43}$$

The standard solution technique takes the Fourier transform of the initial packet to go from $\psi(\underline{x}, 0)$ to $\tilde{\psi}(\underline{k}, \omega)$. The wavefunction is then propagated forward in the frequency domain to time t and transformed back to the time domain to obtain $\psi(\underline{x}, t)$.

The result in Eq. 43 is peculiar in two respects. First, it is an epistemic result that hinges on the initial conditions at $t = 0$, but it does not smell right as an ontic description of W-state diffusion for a free quanton. According to Eq. 43, the variance is nearly constant for small t but then eventually grows quadratically for large t. A linear variance growth rate of $\hbar/m$ at all times seems at least as plausible an ontic model. Second, $\Delta(t)$ is a symmetric function of time, implying that the state at $t = 0$ is special and qualitatively different from states at all other times.

The concept of micro-measurements offers an alternative picture and prediction of how a free quanton evolves. In this view, the evolution is governed by a continuous interplay of Q-1 dynamics, which are conducive to wavepacket expansion, and Q-2 dynamics, which tend to shrink the wavepacket and prevent the quanton from straying far from a classical particle-like form and behavior. The Q-2 dynamics effect *continuous spontaneous localization* (CSL), which is central to the idea of physical wavefunction collapse in the GRW approach to quantum theory.

Whereas Q-1 by itself predicts wavepacket expansion, the micro-measurements model predicts that the free quanton executes a random walk, with the wavepacket maintaining constant width on average over time. In

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[48] Except in highly rarefied experimental settings that produce mesoscopic quantum states.

[49] The lone exception is the Airy wavepacket, which is a theoretical curio because it accelerates.

principle, the two are experimentally distinguishable, since the micro-measurements model predicts an upper limit to the scales at which quantons can exhibit quantumness.

3.6.5 Time-Dependent Perturbation Theory

Quantum mechanics calculates transition rates for spontaneous emission by appealing to time-dependent perturbation theory (TDPT), which attempts to extend the Rule 1 formalism to encompass non-conservative interactions with the environment. In TDPT, a time-varying perturbation term is added to a time-invariant baseline Hamiltonian, and the wavefunction solution is expressed as a linear combination of the baseline eigenstates with time-varying coefficients.

The mathematical formalism of TDPT is couched entirely in terms of Rule 1, and the resulting solution is ostensibly an uncollapsed wavefunction. However, the conventional treatment then goes on to speak of transition rates as probabilities per unit time. The well-known Fermi Golden Rule derives the probabilities by applying the Born Rule to the uncollapsed wavefunction.

Wavefunction solutions of time-invariant Schrödinger equations are long-lived and can wait until eventual measurement events before the Born Rule need be applied. Not so with solutions of time-dependent Schrödinger equations. Quantum mechanics is only able to make practical use of the TDPT wavefunction solutions by applying the Born Rule shortly after the Hamiltonian perturbation begins to take effect. Rule 2 physics becomes inextricably drawn into the picture, even though the Hamiltonian formalism is intended to be Rule 1 only.

The upshot is that TDPT does not rest on a sound foundation in that it exceeds the scope limitations of Q-1, which is naturally suited only for conservative interactions with the environment. It is an outstanding challenge of Q-2 to explain the Fermi Rule more deeply.

4 New Quantum Framework vis-à-vis Other Interpretations

Various interpretations of quantum mechanics that have been proposed over the decades. *Interpretation*, however, is a misnomer; they are really different physical *theories*. They all attempt to explain how and why quantum mechanics works, but they go about filling in the details differently. Several, but by no means comprehensively all, are discussed in this section.

4.1 Pilot Wave Theory

The central contention of pilot wave theory [8] - first proposed by de Broglie in the late 1920's and later developed by Bohm (1952) - is that the electron ontology is primarily that of a classical point particle. The pilot wave is essentially an elaborate force law that can reproduce the interference pattern in the two-slit experiment. Whereas the new framework posits a combination of W-state and P-state, Bohm took the conjunction of wave and particle literally.

4.1.1 Pilot Wave Theory - Force Law

The conceptual simplicity of pilot wave theory comes at the price of complicated requirements on the force field. It is first noted that an interference pattern is much more elaborate than spatial arrival distributions resulting from simple familiar types of classical force laws, such as Coulomb attraction of the electron to the lensing wire. Conversely interpreted, it takes a complicated force law to produce the interference pattern. While that does not violate any fundamental tenets of classical physics, it begs the question of the physical origin of such a force field. Is it of electromagnetic origin or related to the specific nature of the experimental configuration (e.g., materials used)? That seems improbable, since the lensing and interference effects can be achieved by many experimental configurations and techniques. They span a diverse range of underlying physical principles (*e.g.*, at one extreme, gravitational lensing) and can employ a wide variety of particles other than electrons, including small and large molecules, which are electrically neutral. In all cases, interference phenomena can be produced under the right conditions.

The interference pattern exhibits a quantitative feature that is of universal character. The spacing between interference fringes is characterized by a wavenumber parameter, k, that is directly proportional to the particle momentum, p, measured at the detection site, as in Eq. 15b. Planck's constant, $\hbar$, surfaces in all realizations of the two-slit experiment.

In the pilot wave framework, any physical theory of the force field must account not only qualitatively for the existence of interference phenomena but also quantitatively for the relationship in Eq. 15b. It must incorporate $\hbar$ integrally into the mathematical fabric of the theory. Furthermore, in the limit of $\hbar \rightarrow 0$, it must reduce to the conventional classical physics describing the lensing mechanism and the experimental configuration. It therefore splinters into a diverse multitude of separate classical theories, each accounting for one of many techniques of implementing the two-slit experiment.

4.1.2 Difficulty of the Particle Ontology

The splintering frustrates the quest for a simple unified explanation of the central phenomenon exhibited in all implementations the two-slit experiment. The essential source of difficulty in the pilot wave framework is that $\hbar$ is entirely extrinsic to point particles and must be incorporated into the force laws.

The new framework departs from Bohmian mechanics in that it rejects the hypothesis of a particle-like electron ontology. It instead posits an ontology that is *primarily* wave-like. In this view, $\hbar$ is built into the electron ontology and dynamics, whence the electron *is* spread out spatially during its journey through the apparatus and passes through both slits, as opposed to one or the other. The interference phenomenon is no longer regarded as the result of a force field extrinsic to the electron, but instead, as interference of the electron with itself. In this respect, the realist formulation is closer to the conventional wavefunction-based tale of what happens than to Bohm.

With a wave-like ontology, the force field can be modeled in simple conventional form. The interference pattern naturally emerges, and there is no need for modification or fusion of the classical theories of the force fields.

4.1.3 Quantum Potential

Bohm was unable to formulate pilot wave theory entirely in terms of a classical force acting on the particle. Bell later showed that that was no accident, because local hidden variables models are fundamentally incompatible the experimental facts. Bohm's model could reproduce the facts only with the introduction of an extra force term called the *quantum potential*.

The quantum potential is conceptually similar to P-state in the new framework in that it is explicitly non-local and contextual (*i.e.*, globally aware of and responsive to all possible types of measurement-like interactions with the environment). However, the non-local workings of the quantum potential were left as unexplained mystery. The quantum potential was not rooted in any new fundamental theory of causal structure that could explain how non-locality would work. The concept of P-state in Q-2 handles non-locality more naturally and ably, and on a sounder footing, than the Bohm theory.

4.1.4 Particle Trajectories

Despite its limitations, Bohmian mechanics makes an important lasting contribution in that it introduces the notion of particle trajectories in W-state and shows how they can be modeled and analyzed within the Hamilton-Jacobi formulation of mechanics. In the new framework, particle trajectories are interpreted as threads (*i.e.*, paths of causal connectivity), rather than particles as such.

There are some technical differences in the trajectory dynamics of pilot wave theory and the new framework. In the pilot wave theory, the trajectories emerge as the solutions of Hamilton-Jacobi equations formulated jointly in terms of an action field (S) and a density field (R). That way, the particle paths cluster in regions where R^2 (which equates to ρ in Eq. 6a) is greatest, thereby reproducing the statistical outcomes of the Born Rule. The new framework adopts the more general and flexible approach of physical optics, based on Eq. 18.

4.2 Many Worlds

The central contention of Many Worlds - first developed by Everett (1957) and later championed and popularized by DeWitt - is that quantum theory can be formulated *entirely* in terms of Rule 1.

4.2.1 Primacy of the Wavefunction

The new framework concurs with Many Worlds that the dynamics of quantum state evolution is predominantly wave-like, that Rule 1 physical law is meaningful and important in its own right, and that all objects large and small can be described in terms of wavefunctions. Everett deserves historical credit for advancing the idea that the wavefunction itself is ontically real. The new framework differs only on the matter of W-state versus the wavefunction *per se*.

4.2.2 Wavefunction Branching

Many Worlds takes an extreme approach to the measurement problem by doing away with Rule 2 altogether. It maintains that unitary evolution of a single universal wavefunction continues unbroken forever. Everything that can happen does happen in that potentia embedded in the wavefunction are never destroyed.

Many Worlds denies that there is any such thing as a measurement event, including when a conscious observer obtains a seemingly definite and unmistakable outcome in the laboratory. According to Everett, the interaction between observer and observed system precipitates a splitting of the universal wavefunction into two or more branches[50], in which they become mutually entangled. One branch contains the here-and-now universe, in which the specific manner of phase relationships produces the apparent result of just the one observed outcome. Other branches contain different phase relationships that produce the other possible outcomes. The proliferating branches comprise terms in a stupendously complicated universal wavefunction.

4.2.3 Does Many Worlds Solve the Measurement Problem?

Many Worlds is sometimes characterized as the austere interpretation of quantum mechanics in that it is based entirely on Rule 1 and takes it to its untrammeled logical conclusion. By doing away with Rule 2 and particles, it eliminates the split character and landscape of quantum theory and lays claim to parsimony. For these reasons, many theorists find it attractive.

But does Many Worlds solve the measurement problem, or does it sweep it under the rug by shunting the unobserved outcomes into parallel universes? It is noted that Many Worlds does nothing to simplify explanation of the phenomenological reality in the one here-and-now universe in which the whole of physics, as far as we will ever be able to tell, actually lives. Moreover, the parallel universes, according to advocates, do not entirely vanish into oblivion; they can resurface and interfere with the here-and-now world. Many Worlds therefore does not lessen the need to account for entanglement obligations.

Rule 1 physics, as conventionally formulated (and accepted by Everett), is plagued by difficulties and contradictions vis-à-vis measurement issues. Many Worlds and TDPT both strive to be Rule 1 only, but in practice, they are forced to invoke the Born Rule (or what is essentially the same, in selecting one wavefunction branch pairing over others) to account for the phenomenology of the here-and-now world.

Pure Rule 1 dynamics are deterministic and reversible. It therefore cannot, in its own terms, provide the catalyst mechanisms that precipitate branchings. Furthermore, reversibility implies that branches can merge and coalesce as readily as they can split and proliferate.

4.2.4 Many Worlds Complexity

Many Worlds makes no pretense of complexity control. It implies that quantum physics, based on what is known for certain about it, is so intractable that it cannot fit into one 4D world of the familiar kind. It thus fails on the story-telling questions. It pitches the notion of a universal wavefunction, but says nothing about how science would ever be able to construct or make use of a practical working representation of it.

It has been pointed out that the new framework concurs with Many Worlds on the primacy and ontic stature of the wavefunction, except for the distinction between W-state and the wavefunction. Even that, however, is a noteworthy difference. Because W-state is a function on the joint time-frequency domain, it has many more degrees of freedom than the wavefunction, which is a function on the time domain. It thus has far more capacity to embed potentia within the one here-and-now world of 4D spacetime, obviating the parallel universes.

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[50] Since Many Worlds posits a universal wavefunction, the here-and-now universe must be described in terms of wavefunction branches.

4.3 Objective Collapse Theories

Objective collapse signifies a class of theories that posit that wavefunction collapse is an objectively real physical process. The best known of these is Continuous Spontaneous Localization (CSL), which is a fusion of the work of Pearle with that of Ghirardi, Rimini, and Weber (GRW).

4.3.1 Coexistence of Rules 1 and 2

GRW takes a view toward measurement that is diametrically opposite Many Worlds. The main motivating idea of objective collapse theory and research is that Rule 2 physics should be taken seriously as a real and important feature of the quantum landscape. It maintains, as does the new framework, that Rules 1 and 2 coexist in nature and must be harmonized in a single theoretical framework.

GRW is the only well-known approach to quantum theory that embraces the concept of micro-measurements. CSL modifies standard quantum theory to accommodate spontaneous micro-measurement events, which are characterized by a certain probability, per unit time per unit spatial volume, of collapse precipitation.

4.3.2 Micro-Measurement Model Parameters

One difficulty with CSL is that introducing new Q-2 physics typically comes at a cost in model complexity. Consider just the simple example of micro-measurement processes involving free quantons. The micro-measurements hold the time-averaged spatial width of the W-state to constant size and cause the quanton to execute a random walk. But what is that width value? It cannot be the Compton wavelength, $\hbar/mc$, as that is too small; the velocity components of the wavepacket would then be on the order of c, and the quanton would not be well-localized. The width must be the Compton wavelength times some scaling factor, which is essentially an arbitrary parameter introduced into the Q-2 theory.

It has been noted that in standard quantum theory, the only mathematical substance of Rule 2 is the Born Rule and the projection operator formalism. It is ideally parsimonious and parameter-free. Rule 1 is nearly so in that it introduces only one new constant of nature, $\hbar$. It falls short of ideal parsimony only in that it offers no explanation of the particular value of the fine structure constant, $\alpha = e^2/4\pi\epsilon_0\hbar c \approx 1/137$.

4.3.3 General Theory of Measurement

It has been pointed out that externally and internally triggered measurement events are essentially the same in their effects on the quanton dynamics. This implies need for a broader view toward CSL, conducive to its inclusion in a more comprehensive theory of measurement processes.

4.4 Copenhagen

Copenhagen needs no introduction. For a century now, it has been, and remains, the orthodox dispensation, although Many Worlds has gained ground in recent decades and become influential with a wide following.

4.4.1 Standard Quantum Theory

Distinction must be made between standard quantum theory and the standard *interpretation* of quantum theory. The former encompasses the established experimental fact and phenomenology, in conjunction with the Hilbert space formalism originally presented by von Neumann in *Grundlagen* (1932).

In favor of standard quantum theory is the fact that it has unfailingly proved *correct*, despite the century-long disarray on the foundational issues. The new framework now provides insight into *why* it works: it works because it makes contact with underlying deep realities of nature. Austere quantum mechanics can be regarded as those aspects of the standard formalism for which the new framework provides a rigorous ontic footing, including: (*i*) the Hilbert spaces, which represent the sets of square-integrable W-state distributions on rest manifolds, (*ii*) the Schrödinger and Dirac equations, wherein the Hamiltonian is in Heisenberg matrix form, and (*iii*) the Born Rule.

4.4.2 Dogmatic Anti-Realism

The Copenhagen dispensation (*i.e.*, the standard interpretation) is well-known for its hard-line anti-realist dogma, which maintains that human ability to fathom and visualize the quantum world or to think outside the confines of classical language was fundamentally limited - indeed, downright impossible. That was the deeply-rooted conviction oft expressed in no uncertain terms by Bohr and Heisenberg, who were both schooled in Kantian philosophy[51].

Anti-realism stemmed from the historical circumstances of the difficult birth of quantum physics. If its conceptual intractability seems any less now, it is only because we have had a whole century to think about it. The 1920's, however, did not have the benefit of the experimental and theoretical insights that have immensely illuminated our 21st-century understanding. Physicists at the time were in need of a working theory, but the founders did not have good answers to the hard foundational questions. The historical result was that anti-realist sentiment took root and became the dominant way of thinking in 20th-century physics. Practitioners had a bag of tools that worked, and they followed the path of least risk and resistance, which in truth was the only known viable path forward at the time (and for the most part still is).

Anti-realism, in the historic quantum context, does not simply mean sticking to the facts and established calculation tools, and eschewing metaphysical conjecture and speculation. Under Bohr, Heisenberg, and Rosenfeld, anti-realism hardened into an explicitly obscurantist dispensation that actively discourages and shuns inquiry that seeks to understand quantum mechanics more deeply than the fact that it works as a practical tool in the laboratory. They maintained that quantum theory as of 1930 was a done deal and closed book[52]. The anti-philosophical stance maintains that it is altogether futile and meaningless, as a matter of fundamental principle, to seek clarity and understanding on basic questions of what, where, when, and how.

4.4.3 Instrumentalism

Realism and *instrumentalism* signify opposite views on the purpose, capabilities, and methods of science. Realism[53] holds that the principal objective of science is to discover and elaborate theories that are deeply rooted in fundamental principles that make contact with and reflect the bedrock reality of nature. Instrumentalism regards that - unless it is within reach of direct observation, experimental testing, or everyday experience - as too ambitious, speculative, and prone to fruitless forays into metaphysical conjecture. It advises sticking to the experimental facts and the mathematical cookbooks. For the cookbooks to predict experimental outcomes and account for phenomenology is all that can be asked or expected of science; it is therefore misguided and unscientific to seek deeper explanation of what the cookbook formalism means or why it works.

The viability of an instrumentalist approach rests on the assumption that the cookbook is reasonably simple in its mathematical content and based on a small set of well-established principles and laws. It then becomes all a matter of application, *i.e.*, "shut up and calculate". In practice, that works well in many fields of science and engineering, the most spectacular historical example being classical thermodynamics. It is an extremely practical toolkit that covers a vast gamut of established facts and phenomenology based on a bare minimum of macroscopic concepts (energy and entropy) without appealing to any models of the microscopic composition of matter.

4.4.4 Implications of the Unsolved Foundational Issues

Quantum mechanics had a remarkably good run in the middle decades of the 20th century, but the instrumentalist style of scientific enterprise now appears to have worked only up to a point. It is fair to ask whether the foundational issues have caught up with quantum mechanics and ultimately slowed progress in fundamental physics in the half-century since the Standard Model.

Unlike classical thermodynamics, the quantum cookbook formalism is not at all simple and fixed. The mathematics is not given or set in stone *a priori*; it springs from the minds of physicists who are continually trying to imagine what the quantum world is like and to craft expression for it in Hamiltonians and Hilbert space structures. In practice, however, the lack of realist roots and foundation too easily allows the mathematics to take on a life

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[51] Kant believed that mankind - and by extension, the scientific method - was inherently limited in its ability to learn about and comprehend nature, because human sensory apparatus and intelligence were originally purposed for mundane needs of survival. [7]

[52] Ironically reminiscent of the pre-1900 confidence that physics was on the cusp of completion.

[53] This is different from the narrower meaning of *realism* pertaining to the pre-measurement status of dynamic attributes.

of its own; Dirac historically was one of the first examples. Feynman maintained that QED calculations, despite the questionable expediency of renormalization, were self-justifying as long as they produced answers that agreed with experiment. But researchers have historically produced a number of different calculational paths, rooted in dissimilar physical and mathematical assumptions[54], that have all led to ostensibly fantastic agreement with experimental results for the Casimir effect [21] and the Lamb shift [3]. When symbols in the calculations are regarded as means to the end of obtaining correct or viable answers, and the reality status of those symbols is unsettled and regarded as unimportant and incidental, standards for what constitutes good science - as opposed to speculative fantasy, bad numerology, or expedient manipulation of the models - become stretched and deteriorate.

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[54] There is no definitive repository of publicly available source code for the QED calculations of Feynman, Schwinger, or Bethe.

References

[1] A. Becker. *What is Real? The Unfinished Quest for the Meaning of Quantum Physics*. 2018.

[2] S. Carroll. *Something Deeply Hidden: Quantum Worlds and the Emergence of Spacetime*. 2019.

[3] O. Consa. “Something is Wrong in the State of QED”. In: *ArXiv e-prints* (2021). arXiv: `2110.02078`.

[4] P. Davies. *Other Worlds: A Portrait of Nature in Rebellion*. 1980.

[5] O. Freire. *The Quantum Dissidents: Rebuilding the Foundations of Quantum Mechanics (1950-1990)*. 2015.

[6] J. Gribbin. *Schrödinger’s Kittens and the Search for Reality Solving the Quantum Mysteries*. 1995.

[7] N. Herbert. *Quantum Reality: Beyond the New Physics*. 1987.

[8] P. Holland. *The Quantum Theory of Motion: An Account of the de Broglie-Bohm Causal Interpretation of Quantum Mechanics*. 1995.

[9] R.I.G. Hughes. *The Structure and Interpretation of Quantum Mechanics*. 1992.

[10] M. Jammer. *The Philosophy of Quantum Mechanics*. 1974.

[11] M. Kumar. *Quantum: Einstein, Bohr, and the Great Debate about the Nature of Reality*. 2008.

[12] D. Lindley. *The Myth of a Unified Theory*. 1993.

[13] W.E. Maudlin. *Philosophy of Physics: Quantum Theory*. 2019.

[14] G. Musser. *Spooky Action at at Distance*. 2015.

[15] H. Ohanian. *Gravitation and Spacetime*. 1976.

[16] C. Rovelli. *Helgoland: Making Sense of the Quantum Revolution*. 2020.

[17] R. Shankar. *Principles of Quantum Mechanics*. 1994.

[18] L. Smolin. *Einstein’s Unfinished Revolution: The Search for What Lies Beyond the Quantum*. 2019.

[19] L. Smolin. *The Trouble with Physics: The Rise of String Theory, The Fall of a Science, and What Comes Next*. 2007.

[20] L. Susskind and G. Hrabovsky. *The Theoretical Minimum: What You Need to Know to Start Doing Physics*. 2013.

[21] A. Wallace. *Choosing Reality: A Contemplative View of Physics and the Mind*. 1989.