A New Foundation for Standard Quantum Theory: Refinement and Prelude to Quantum Gravity

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Abstract

This paper elaborates upon and further develops https://vixra.org/abs/2402.0149, which proposed a novel realist framework for making sense of standard quantum theory. The framework is said to be "realist" in that it provides a complete observerless picture of quantum state ontology and dynamics, in conjunction with a mechanistic account of measurement processes, that answers basic questions of what, where, when, and how.

The framework embodies a general quantum ontology consisting of two entities, called W-state and P-state, that respectively account for the wave- and particle-like aspects of quantum systems. 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 is a non-local hidden variable that constrains the probability distributions governing deferred measurement outcomes, such as in the Einstein-Podolsky-Rosen (EPR) thought experiment. This paper presents a full solution of the core measurement problem, which pertains to the global coordination within quantum systems required to bring about wavefunction collapse in causal fashion consistent with special relativity.

The framework has a tri-partite structure, consisting of Q-1 (unitary evolution of W-state), Q-2 (measurement-like events that continually occur in the absence of observer intervention), and Q-3 (measurement events in experimental settings). Traditional quantum theory draws a sharp dichotomy between Q-1 and Q-3. The new framework incorporates physical wavefunction collapse, which is held to be a real physical process and ubiquitous feature of nature in the quantum realm, as Q-2, which fills the gap between Q-1 and Q-3.

Quantum systems have a built-in dynamic proper time, which is relativistically invariant and plays a central role in the measurement problem solution. The framework is thus background-independent, a key requirement for making quantum theory compatible with general relativity. Quantum gravity is introduced as Q-4 atop the tri-partite foundation.

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1 Introduction

1.1 Rules 1 and 2

The traditional pedagogic presentation of quantum mechanics is essentially a cookbook for predicting the outcomes of experiments. It can be summarized in terms of a split formalism consisting of two rules.

Rule 1[1] accounts for the evolution of a quantum system between measurement events, ostensibly when nobody is looking. More precisely, it accounts for only the experimenter's *knowledge* of the quantum state, vis-à-vis its usefulness in predicting outcome probabilities for any experiment that could be performed on the system at some future time. That knowledge is represented as a wavefunction, which is necessarily a wave-like entity because interference effects figure centrally in explaining the statistical patterns observed in quantum phenomena.

Rule 2 yields the probabilities of the various possible values that can be obtained for any dynamic attribute that the experimenter chooses to measure. This is the well-known Born Rule, which yields outcome probabilities that depend on (*i*) the wavefunction, unitarily evolved forward to the time at which the measurement is conducted, and (*ii*) the operators that project the wavefunction onto the eigenspaces associated with the attribute being measured.

1.2 Tripartite Structure of Quantum Theory

The realist framework advocated in this paper consists of three parts, or tiers, named Q-1, Q-2, and Q-3.

- **Q-1** embodies the essential features and physical content of Rule 1. In https://vixra.org/abs/2402.0149 [11] (henceforth referred to simply as the "previous paper" by this author), the concept of W-state was introduced as an ontic generalization of the wavefunction. That is, it represents an objectively real wave-like entity and state of nature that exists between measurement events, irrespective of the existence of observers. Q-1 is concerned exclusively with (*i*) the ontic structure of W-state and (*ii*) the deterministic (unitary) evolution of W-state between measurement events.

- **Q-2** encompasses processes that are non-deterministic but do not involve interactions with external surroundings (*e.g.*, macroscopic measuring devices). It spans a wide range of well-known phenomenology, including atomic phenomena (*e.g.*, spontaneous emission, zitterbewegung), tunneling (*e.g.*, radioactive decay), and decoherence.

- **Q-3** embodies the essential features and physical content of Rule 2, as it has been traditionally expressed and understood. It deals principally with measurement processes in the context of contrived experimental interventions, which are the primary focus and concern of traditional quantum theory.

- Q-1 and Q-2 together describe in the ontology and dynamics of isolated quantum systems[2]. They jointly describe a non-deterministic world, in which quantum interference effects and fluctuations are both paramount and in constant interplay with one another.

- Q-2 and Q-3 together encompass measurement-like[3] processes, which account for all forms of departure from the smooth deterministic dynamics of Q-1.

Although Q-2 occupies well-trodden ground covered extensively in both introductory- and advanced-level textbooks, the traditional pedagogy is not clear about precisely how any of that phenomenology fits between Q-1 and Q-3. Indeed, it is highly ambiguous, such as on the basic question of whether measurement-like processes of any kind occur in the absence of obvious acts of intervention. Do irreversible bifurcation[4] events actually occur in individual systems, or does unitary evolution continue indefinitely?

The traditional pedagogy regards Rule 2 as exceptional in nature, *i.e.*, an *ad hoc* departure from the tidy self-contained formalism of Rule 1. It explicitly recognizes such departures only in well-defined experimental

[1] This terminology is borrowed from Smolin [18]. It is similar to von Neumann's terminology of Type I and Type II processes.
[2] Because of non-locality and entanglement, the definition of a quantum *system*, much less an isolated system, is not trivial.
[3] The term *measurement-like* emphasizes transcendence of the narrow traditional scope of measurement in laboratory settings.
[4] A bifurcation in which only one path is taken (unlike in Many Worlds).

settings when an observer intervenes and obtains a definite[5] actual outcome. Otherwise, it declines to pinpoint any irreversible bifurcations as such, even in dynamic scenarios in which branches of the wavefunction evolve divergently. It follows from that non-commital stance that Rule 1 dynamics take precedence by default, and that therefore, a radioactive nucleus evolves into a superposition of decayed and undecayed states. The superposition ends only when an observer opens the box to see whether the Schrödinger cat is alive or dead.

A primary motivation for the proposed tripartite structure is to bring clarity to the middle ground. The unifying theme of Q-2 is that all of the phenomenology that it encompasses can be regarded as manifestations of *physical wavefunction collapse*, which is held to be a real physical process and feature of nature in the quantum realm. Q-2 represents its incorporation into a comprehensive realist framework of quantum theory.

The framework maintains that the scope conferred to Rule 1 by conventional quantum theory is too broad, whereas the scope conferred to Rule 2 is too narrow. The tale of the cat is a parody[6] of the excessive credence in unitary evolution under Rule 1, unbuffeted by decoherence.

1.3 Mainstream Quantum Theory

This paper speaks of "mainstream" quantum theory in several ways, which reflect differences of historical context and relation to the new realist framework.

Traditional quantum theory signifies the historic distillation of quantum mechanics, as it came to be understood, applied, and taught throughout most of the 20th century. That distillation, of course, was shaped and influenced most significantly by Bohr.

Conventional quantum theory is, for the most part, synonymous, but emphasizes those facets of the traditional understanding that continue to hold sway in the 21st century. At least two differences are noteworthy. First, the Copenhagen dispensation is no longer the airtight monopoly of mainstream thought that it once was. Second, recent times have benefitted from a wealth of new experimental capabilities, specialized avenues of inquiry (*e.g.*, in quantum optics and quantum information science), and theoretical progress (*e.g.*, in understanding of decoherence).

Standard quantum theory signifies those aspects of the conventional formalism and understanding with which the realist framework concurs, but with which Einstein, for the most part, did not (*e.g.*, issues of determinism, locality, and hidden variables). A major objective and obligation of the realist framework is to explain *why* quantum mechanics works, despite its strangeness and conceptual intractability. In doing so, it gives fresh new expression to many a tenet of quantum mechanics that has been vindicated by experiment.

1.4 Q-1 and W-state

Because the topic of measurement is so centrally important in quantum physics, a full solution to the core measurement problem must be presented before Q-2 and Q-3 can be developed any further.

The concept of W-state was introduced and developed in mathematical detail in the previous paper [11] and will not be repeated. Only key points, apropos the role of W-state as a logical prerequisite to treatment of the core measurement problem, are made in this paper. A summary of key points:

- W-state is a field-like entity whose local reality, at any point in space-time that it occupies, consists of a superposition of quantum wave elements writ small. In this respect, it is a fundamentally novel type of non-classical entity that is represented mathematically as a function on the joint time-frequency[7] domain, whereas local realities in classical physics are represented as tensor fields that are ontically primary in the time domain.

- Quantum wave elements are *relational* in a specific sense that does not arise in classical physics or familiar logic. 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. A quantum wave, by contrast, has no crests, troughs, or zeros. Its ontology is such that it is meaningful only to speak of phase differences between values at two different points. Because of the relational nature of W-state, complex-valued quantities enter the mathematical description in an inextricable and distinctly non-classical way, such that their real and imaginary parts have no meaning by themselves.

[5]The definiteness, according to the Copenhagen dispensation, can be averred only by a conscious being.
[6]Ironically, a parody of the excessive scope conferred to Schrödinger's own equation.
[7]This is abbreviated reference to the space-time and wavenumber-frequency domains of function representation.

- Q-1 is the core theory governing W-state dynamics. Like Rule 1, it is a stand-alone wave theory. It can be regarded as a generalization of the Schrödinger and Dirac equations. The W-state dynamics are formulated in terms of world-line trajectories, called *threads*, whose evolution is deterministic and formally akin to Newton's Second Law.

- For any two threads that intersect at a space-time point but are different by virtue of their different wavenumbers (velocities), the relational ontology makes meaningful their phase difference and amplitude ratio at the point of intersection. Additionally, the relational ontology countenances the notion of phase difference between any two points on a common thread, which is derivable from an action integral. The Lagrangian integrand accounts for the conservative forces acting on the system between measurement-like events.

- In conventional quantum theory, the Schrödinger wavefunction, $\psi(\underline{x}, t)$, is a function on the time domain, as opposed to the time-frequency domain. It follows that the quantum wave elements, which are the Fourier coefficients of ψ, correspond to straight-line thread trajectories of infinite extent. In this respect, they are rigid[8], whereas threads can curve, bend, and adapt flexibly to varying local conditions.

- As solutions of Hamilton's equations, threads are akin to particle trajectories in pilot wave theory. Particles, however, are not part of the Q-1 ontology as they were in Bohm's theory[9]. Q-1 can potentially leverage certain insights from Bohmian mechanics, the most important of which is that the Born Rule follows as a deductive consequence of the assumption of an ensemble of systems in which the initial W-state is in equilbrium.

- A key emergent feature of W-state is *rest manifolds*, which furnishes an invariant definition of proper time within a quantum system as a whole. They amount to a built-in ether within W-state that is compatible with special relativity. Rest manifolds serve as synchronization surfaces, on which W-state changes non-locally amidst measurement-like events[10] that impinge on the system anywhere on the manifold.

- The term *quantum system* means either a single quanton[11] or a set of quantons connected by relational ties. The concept of rest manifolds applies to both.

- W-state contains all the information needed to predict the outcome probabilities for any type of measurement process to which an isolated quantum system could be subjected at some future time. It is emphasized that the probability distribution functions apply to the system, *as an isolated system* (*i.e.*, irrespective of correlations in the measurement outcomes with those obtained for other systems with which it is entangled).

- In general, W-state changes discontinuously, non-locally, and non-deterministically across rest manifolds amidst measurement-like events. The particle-like aspects of quantum ontology exist as global properties of the W-state that are conserved in measurement-like processes (*i.e.*, hold for both the pre- and post-measurement W-state configurations).

- The W-state can be modeled and treated rigorously as a function of proper quanton time. The set of W-state configurations on a rest manifold is a Hilbert space of square-integrable functions. The temporal evolution of the W-state, expressed with respect to a set of basis functions spanning the Hilbert space, amounts to an *interpretation* (in a true sense of the word) of Heisenberg's matrix mechanics in the realist framework.

- Hilbert spaces, the first chapter in many a quantum theory texbook, have two key roles in the realist framework. One is in the description of local W-state, which consists of superpositions of quantum wave elements. The other is in the description of global W-state for an entire quantum system on a rest manifold.

1.5 Is the Wavefunction Epistemic or Ontic?

Conventional quantum theory takes an ostensibly instrumentalist view toward the wavefunction. It maintains that it is an epistemic construct that is meaningful only as a means to the end of predicting measurement outcome

[8]One manifestation of the rigidity is reliance on phase cancellations at the periphery to make the wavefunction square-integrable.
[9]Bohm and de Broglie took the conjunction of wave and particle literally.
[10]The term *event* still holds in the sense of relativity, meaning something localized in space-time.
[11]*Quanton* is the generic term introduced in the previous paper [11] for an indivisible quantum system (*e.g.*, electron, photon).

statistics. But can it fairly and honestly be said to bear no direct relation to underlying pre-measurement physical reality?

The instrumentalist working ethos, as it is instilled in students and practitioners, is summed up by the well-known maxim of "shut up and calculate": Learn how to use the mathematical machinery of Rules 1 and 2, but do not try to make sense of it. Refrain from asking or thinking about questions of what, where, when, or how. Instrumentalism, however, assumes that the formalism is a closed book in well-established final form, and that application is all that remains. That, however, is not at all a realistic view how physics is practiced. The quantum formalism, as it is tailored to specific research applications, 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. To accomplish its predictive task, the wavefunction must account for interference effects, from which it follows that it must necessarily be a wave-like entity composed of elaborate structure (*e.g.*, spinor fields, fermionic and bosonic combinations of permutation terms). The wavefunction, ostensibly a mere knowledge model, thus amounts in practice to a full-fledged depiction of an objective quantum reality[12], even though instrumentalism, as a philosophical dispensation, insistently denies that scientific investigation makes any direct contact with deep reality[13].

The realist framework maintains that W-state, as the principal embodiment of quantum systems between measurement events, is a material wave that does carry energy-momentum[14]. This runs contrary to the mainstream view, which regards the wavefunction as an epistemic construct (*i.e.*, probability wave only). That arose historically from the probabilistic interpretation of $|\psi|^2$, which gained favor over Schrödinger's earlier interpretation of $-e|\psi|^2$ as a charge density. That inferential leap was a historical accident that was not logically warranted; the probabilistic interpretation should have supplemented, rather than discredited and replaced, the material interpretation, as both were correct.

2 Core Measurement Problem

The *core measurement problem* is the central question of how wavefunction collapse transpires, from a mechanistic perspective. It is about demystifying and explaining the global coordination that Nature must somehow effect within quantum systems in order to collapse the pre-measurement W-state, which is spatially distributed, in causal fashion consistent with the strictures of special relativity. The collapse process must additionally guarantee that the W-state at all times satisfies certain holistic constraints, which reify the particle-like nature of the quantum system.

2.1 Non-Locality

The realist solution of the core measurement problem, which will be told as a story in what follows, is distinctly and pointedly non-classical in two fundamental respects, both of which deeply troubled Einstein. The more conceptually difficult of the two is non-locality, which Bell and the subsequent experiments have shown to be an undeniable feature of quantum physics.

Non-locality can be most easily accommodated and visualized in the classical setting of Galilean relativity, *i.e.*, special relativity in the limit of $c \to \infty$. Time becomes absolute and decoupled from space. It is then 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*.

The fundamental requirement for non-locality is the existence of absolute (*i.e.*, relativistically invariant) time manifolds, as is the case in Galilean relativity. In the quantum realm, the rest manifolds that emerge from W-state also meet that requirement. However, the strong form of special relativity, which prohibits superluminal signaling, imposes severe information-theoretic restrictions on forms of non-locality that are feasible. The restrictions permit only *weak non-locality*, in contradistinction to strong non-locality.

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[12] From a control-theoretic perspective, the epistemic wavefunction is akin to a full-fledged state estimator (*e.g.*, Kalman filter).

[13] This outook derives from Kant, who 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]

[14] This contention and outlook is a key prerequisite for making the new quantum theory compatible with general relativity.

2.2 Determinism

A remarkable feature of weak non-locality is that it *requires* absoluteness randomness of the quantum kind, as a necessary condition (i) to preclude superluminal signaling, and (ii) to realize strong statistical measurement outcome correlations (*i.e.*, that violate the Bell inequalities). It follows that the second non-classical feature – indeterminism – is a deductive consequence of non-locality.

The abandonment of determinism is a less radical departure from classical physics than non-locality. It is true, of course, that prior to the advent of quantum mechanics, the common understanding of Newtonian physics held that it required determinism, from which the paradigm of a clockwork universe followed. That, however, implicitly assumes that the force laws themselves are all deterministic (*i.e.*, functionally dependent only on the positions and momenta of other particles with which any given particle interacts). However, the causal structure of classical physics does not logically preclude injection of *innovation* (*i.e.*, outcomes of local acts of dice rolling), which, by definition, has no prior causation.

2.3 Realist Account of a Quantum Measurement Process

As an example illustrating the essential aspects of quantum measurement processes, consider the simple scenario of a photon passing through a beam splitter. The W-state splits into two lumps (half-photons), one of which heads in a leftward direction while the other heads rightward. Each half-photon encounters a detector lying in its path.

At the outset, we accept and take to heart Bell's lesson, which rules out any supposition of local hidden variables. There is nothing in either half-photon that predetermines or biases the outcomes at the detectors. The W-states are identical in that anything that can be said about one half-photon, by itself, can be said about the other. However, the two are entangled in that they have a relational tie: either the left or the right half-photon, but not both, will register a positive detection. The detectors are similarly identical and free of hidden variables; they operate mutually independently, with no classical communication channel between them.

Consider first the case in which the detectors are equidistant from the beam splitter. The measurement events then both lie on a single rest manifold, $\mathcal{M}$, which is associated with the whole photon, despite its being split into two spatially separated pieces.

The story of how the measurement process plays out is told in fictionalized terms of computing agents operating locally at each measurement site, in conjunction with $\mathcal{M}$ serving as a medium on which a non-classical information exchange process transpires globally. It is a purely information-theoretic account of how wavefunction collapse can be realized in a decentralized setting and within the strictures of relativity.

The agent at each detector site responds to the arrival of a half-photon by generating two innovation elements, both of which are random values between 0 and 1. The first is called a *gambit*. The gambits generated by the agents are disseminated on $\mathcal{M}$. Gambit arbitration then occurs as the first step of the global information exchange. It establishes an order of precedence (rank) amongst the agents, based on the gambits they drew.

$\mathcal{M}$ acts as a publishing board, on which results of the gambit arbitration are made visible to all measurement sites. In the second step, the local responses at the sites, which depend on their individual ranks, are determined. The highest-ranking site gets first crack to determine its own local measurement outcome. Suppose, for concreteness, that the left detector ranks higher than the right. In the second step, the second innovation element, called for lack of better terminology simply an *index*, determines the outcome at the left detector. A value less than (greater than) 0.5 translates into a negative (positive) detection outcome. The right detector, having drawn the shorter gambit straw, is then constrained to produce the opposite local measurement outcome. The logic generalizes to any number of measurement sites spatially distributed on $\mathcal{M}$.

In a negative detection outcome at a measurement site, the half-photon vanishes upon contact with the detector, ceasing to have any further existence in the vicinity of that site. In a positive detection outcome, on the other hand, the local W-state becomes highly concentrated and intensified; the half-photon becomes promoted to a whole photon.

2.4 Non-Simultaneous Measurement Processes

Consider next the more general case, in which the detectors are not equidistant from the beam splitter. The two measurement events then occur at different proper quanton times. Suppose, for concreteness, that the left detectior is closer than the right detector. In the first measurement event, the left detector generates and disseminates a gambit, which prevails by default because the right detector has not yet encountered the half-photon heading its way. The index drawn by the left detector then determines whether a negative or positive local detection outcome occurs.

That much is simple, but this version of the scenario is more complicated than the previous one because the photon, as a whole quanton, has been only partially intercepted. A definite outcome has been established at the left detector, but the W-state of the right half-photon continues on undisturbed until it encounters the detector in its path. However, the outcome on the right, actualized when the surviving W-state eventually encounters the detector, becomes constrained to be the opposite of the left outcome. It follows that the predictive information content of the W-state is no longer complete.

That was the conundrum that was first exposed in the Einstein-Podolsky-Rosen (EPR) argumentation. The upshot is that some form of spooky action at a distance is required to satisfy both (*i*) the constrained outcome spaces governing deferred measurement events, and (*ii*) weak non-locality.

2.5 P-state

The realist framework holds that spooky action at a distance is mediated as P-state. Once a definite measurement outcome is established at the left detector, that measurement site disseminates onto $\mathcal{M}$ a constraint that applies to all of what remains of the unmeasured W-state.

In its effects on deferred measurement outcomes, P-state can be interpreted and treated mathematically in terms of Bayesian probability theory and belief networks. If a positive detection outcome occurs at the first measurement site, the resulting P-state ensures that a negative outcome will occur at the second site. In this case, the surviving W-state between the measurement events effectively becomes a ghost wave. If a negative outcome occurs at the first site, the P-state ensures a positive outcome at the second site, and so the W-state effectively becomes more potent. Either way, the W-state itself is not physically altered until it encounters the second detector; it is only the odds associated with what will become of it that change.

P-state is conceptually noteworthy in that it vindicates Einstein's contention that quantum mechanics was incomplete. Moreover, it is the only guise in which the realist framework contains hidden variables. Gambit and index values themselves technically do not count as hidden variables because they are produced and consumed entirely on just one rest manifold (*i.e.*, at a single instant of proper quanton time). P-state, on the other hand, endures over finite intervals of quanton proper time and thus act as a supplementary form of quantum *state*.

As a realization of hidden variables, P-state is non-local in a quite literal sense. Unlike W-state and all quantities in classical physics, it is, by its inherent nature, *not* localized and therefore cannot be represented as a function of space-time. P-state, unlike W-state, is technically not a quantum *field*. P-state is what it is only globally on any rest manifold as a whole; it is a function strictly of the proper time of the quantum system.

2.6 Measurement Processes in Multi-Quanton Systems

The preceding analysis applies systems with any number of quantons. A thought experiment scenario with two quantons, for example, is obtained from the following substitutions:

- original photon → pair of electrons in the singlet state
- beam splitter → equivalent device that separates the electrons
- half-photons → whole single electrons
- photodetectors → devices measuring spin alignment along a specific axis

The systems in either scenario, because of their wave-like nature, are distributed in space-time, and the concept of rest manifolds applies to quantum systems generally.

For multi-quanton systems, issues pertaining to the scalability of wavefunction analysis arise because of relational ties. Two quantons, no matter how spatially separated, may bear relation to one another by virture of (*i*) belonging to the same species, or (*ii*) having been in close spatially proximity to one another since either was last measured. In general, analysis of a multi-quanton system is tractable – and a useful source of well-simplified physical insight – only if it proceeds from a W-state model in which the number (N) of quantons is well-defined and finite. Relational ties, however, imply that an exact analysis requires that N be infinite. A W-state model in which N is arbitrarily large gives expression to the concept of the "universal wavefunction", much like that envisaged by Everett and Wheeler.

For the preceding analysis of the core measurement problem to apply to multi-quanton systems, it is necessary to show that the scalability issues are not prohibitive. More precisely, it must be shown that for an isolated system of N quantons, the utility[15] of a W-state model encompassing only the N quantons nearly matches that of the universal wavefunction. If the system is perfectly isolated, the utility, *a fortiori*, exactly matches that of the universal wavefunction.

For a system of N identical quantons, the full wavefunction consists of $N!$ permutation terms. In the rarefied context of analysis of an isolated system (*e.g.*, a helium atom), it may be feasible to regard N as well-defined and finite. In nature, however, N is generally ill-defined and indefinitely large, since natural systems are almost never isolated. The scalability issue is resolved by a roll-off principle, which holds that consideration of only (the typically small and finite number of) quantons with significant local presence in the analysis zone of interest yields, for all practical purposes of analysis, a finite-N W-state model whose utility nearly matches that of the universal wavefunction.

The roll-off principle applies to entanglement just as it does to quanton interchangeability. At a given space-time point $\underrightarrow{x}$, the rest manifold is tangent to the local rest frame of the quantum system, in which the following criterion is met:

$$\int \left|\tilde{\psi}(\underrightarrow{k}, \underrightarrow{x})\right| \underline{k}\, d\,\underrightarrow{k} = \underline{0} \tag{1}$$

Eq. 1, as it was written in the previous paper [11], is for a single quanton, but it readily generalizes to multi-quanton systems. In both cases, the integrand, and therefore the local geometry of the rest manifold, is determined primarily by those quantons whose local spatial presence is greatest. From Eq. 1, it follows that the rest manifold of the universal wavefunction, as it cuts through the analysis zone of interest, is well-approximated by that of the W-state model that includes only the N quantons in the analysis zone.

2.7 Reductionism

A remarkable corollary of the preceding analysis is the fact that it is possible at all to speak of quantum *systems*, of said systems as having parts, and of system isolation, despite non-locality, entanglement, and the holistic and relational properties of quantons. That is possible only because of the roll-off principle, which serves as a practical form of reductionism for analysis purposes, even though reductionism fundamentally does not hold in quantum physics as it does in classical physics.

The roll-off principle can be thought of as a form of Pareto's Law. In general, causes[16] are indefinitely numerous, but not of equal importance. Pareto's Law holds that consideration of only the most important causes, which are often manageably few, suffice to explain effect to a good approximation. Consideration of more causes, in descending order of importance, improves the explanation, but with diminishing returns.

Without reductionism, the ambitions of science would be thwarted by fundamental limitations. The unreasonable effectiveness of mathematics, which Einstein and Wigner both recognized as a *sine qua non* for the prodigious success of the physical sciences since Newton, would no longer hold.

2.8 Is the Wavefunction Complete?

There are two aspects of the incompleteness. The first has to do with the fact that the conventional wavefunction is a function on the time domain, whereas W-state is a function on the time-frequency domain. That makes the former inherently less expressive and flexible than the latter.

The second aspect of incompleteness pertains to the issues brought to light in EPR and was the ground on which Bohr and Einstein disagreed. They were each right in different respects.

On the one hand, the W-state, before it makes contact with any detector element, is complete in the sense envisaged by Bohr. The W-state before the first measurement event is pristinely that of a photon in free transit. It contains no hidden variables that pre-determine or bias the measurement outcomes. The statistical distribution of

[15] The utility of a W-state model is judged by the quality and scope of the predictions and analytic insights it provides.

[16] In the quantum context, "cause" translates to relational ties amongst quantons.

the outcomes, for ensembles of identically prepared systems, is completely determined by the W-state immediately prior to the first measurement. In individual systems, outcomes depend additionally only on innovation produced and consumed on the rest manifolds that intersect the measurement event. It follows that quantum systems, as they exist before measurement, are not *ordinary objects*[17], because their dynamic attributes are not pre-determined. Unless the pre-measurement W-state is already an eigenstate of the attribute being measured, they exist in an objectively real state of indefiniteness.

On the other hand, the W-state is not predictively complete if some other part of the quantum system has already been subjected to measurement. P-state then contains the supplemental information needed for a complete determination of the probability distribution characterizing the deferred measurement. On this point, Einstein was right.

Consider a generic experimental scenario, in which we have prepared an isolated quantum system, know its initial W-state, and keep it isolated until it encounters a certain type of measurement device at some future time. Bohr's claim of completeness holds in that the W-state dynamics alone suffice to predict the probability distribution characterizing the measurement outcomes, *assuming that we do not care about other systems with which our system may have relational ties.* P-state still exists as such and constrains our outcomes, but it has no bearing on the probability distributions governing our measurement outcomes.

If, on the other hand, we know about other systems with which ours is tied, know about measurement outcomes that have been obtained for them, and are interested in correlating our outcomes with theirs, then knowledge of the P-state is additionally required to make a fully informed prediction or retrodiction of the outcomes for our system.

In the EPR scenario, knowledge of the P-state is available only after measurements on the other systems have been performed. If the measurement that we conduct on our system is time-like separated from and comes after the other measurements, then *prediction* is possible (provided that the P-state information is conveyed via a classical communication channel). Otherwise, only *retrodiction* (*i.e.*, after-the-fact comparison of results) is possible.

2.9 Realist Story-Telling

A core requirement of realism is that it satisfies criteria of what it takes to tell a story - a story of how Nature *is*. It must answer basic questions of what, where, when, and how. The story of wavefunction collapse just told does that:

- **What**: The story takes an unambiguously clear stance on the reality status and ontic structure of the quanton protagonist(s), which is described wholly in terms of W-state and P-state. It identifies and makes use of rest manifolds, as an emergent feature of W-state, as key to the explanation of how the fundamentally non-local character of quantum measurement processes can be squared with the strictures of relativity. Additionally, the story pinpoints the interactions between the local detector elements and the impinging lumps of W-state as objectively real physical processes. The detector elements themselves act as observers and can be described in straightforward physical terms, without need to invoke consciousness as a catalyst for collapse. The measurement processes are non-conservative in nature and therefore qualitatively unlike the types of interactions that drive Q-1 dynamics.

- **Where/When**: All activities in the measurement process occur on $\mathcal{M}$ - either locally at the measurement sites or globally as parts of the information exchange. It follows from the combination of local and global activity that the W-state changes discontinuously across $\mathcal{M}$. On the upstream side, the W-state is that of the half-photons in free transit, pristinely unaffected by the presence of either detector element. On the downstream side, on the other hand, it is that of a detected whole photon, which has shown up particle-like at either the left or right detector. The holistic character of the photon is embedded in global properties of the W-state that are upheld on both sides of $\mathcal{M}$.

- **How**: The fictionalized tale, which was told in terms of local computing agents and global information exchange, provides explanation of how wavefunction collapse can be achieved within the strictures of relativity. In this respect, it directly answers the central question of the core measurement problem.

[17]This is a frequent point of confusion. It is often assumed (wrongly) that realist theories can only deal with ordinary objects.

In supplying answers to the basic questions, the realist framework provides a complete visualizable mental picture of the quantum world, with or without observers. A critical aspect of that completeness is that it maps all elements of quantum reality (*i.e.*, the what) to the causal structure of space-time.

2.10 Irreducible Features of the Realist Explanation

The realist story of quantum measurement answers the basic questions of narration, but it has several irreducible features for which it cannot provide deeper explantion: (*i*) sources of absolute randomness, (*ii*) whereabouts of global information exchange activity, and (*iii*) natural computation.

It was shown that absolute randomness is necessary to square non-locality with the information-theoretic strictures of relativity. However, the question of *how* Nature can innovate, without any prior causation, is left unexplained.

Global information exchange involves dissemination of information on $\mathcal{M}$ as an irreducible whole, with no meaningful notion of where on $\mathcal{M}$ the information is stored or how it moves. The realist framework accepts this as an irreducible feature of non-locality and calls for us to disown the notion of space *as a barrier*[18] to the information exchange.

The term *natural computation* gives metaphoric expression to the fact that, as part of the global information exchange, Nature performs extremely complicated forms of non-local computation that stump the capabilities and paradigms of human computing technology. It is the question of what Nature must do to implement the Born Rule, *i.e.*, to select an actual outcome, in an individual system, that conforms statistically to a certain probability distribution. The realist framework cannot answer that[19]; the narrative simply accepts that it can and does happen.

3 Q-1 and Q-2: Quantum Physics between Measurement Events

Q-1 and Q-2 together describe the quantum world without observers, *i.e.*, in the absence of physics laboratories, physicists, and other conscious beings. It describes a non-deterministic world, in which quantum fluctuations are paramount, and properly recognized *as* fluctuations.

Q-2 encompasses a wide range of phenomenology, much of which is well-trodden textbook subject matter. Examples include spontaneous emission from excited atomic states, zitterbewegung (*i.e.*, fluctuating atomic electron dynamics, including in the ground state), and all forms of tunneling phenomena (*e.g.*, radioactive decay). Such phenomena exemplify what were called "micro-measurements" in the previous paper [11]. They are fundamentally similar to measurement events resulting from experimental intervention (*i.e.*, encompassed by Q-3) in that they transpire on rest manifolds and are non-deterministic and non-local. Unlike experimental interventions, however, they occur ubiquitously in nature and are spontaneous (*i.e.*, do not involve interactions with any external systems). They are therefore, for all practical purposes, integrally part and parcel of the dynamics of isolated undisturbed systems.

3.1 Physical Wavefunction Collapse

The realist framework maintains that all Q-2 phenomena are manifestations of physical wavefunction collapse, such as envisaged in the theories developed by Bub, Pearle, and Ghirardi-Rimini-Weber (GRW).

The notion of wavefunction collapse has never been easily accepted – not only because of its *ad hoc* departure from the Rule 1 formalism and non-locality concerns, but also because it implies extreme difference between pre- and post-measurement W-state on the two sides of a rest manifold. It is true that the spatial extent of W-state does have great dynamic range and can indeed change by many orders of magnitude in a single position measurement process. However, micro-measurement[20] processes generally do not span such wide dynamic range.

In the realist framework, collapse does not mean collapse literally to a point. The post-measurement W-state is subject to the uncertainty principle, from which it follows that it cannot be pinched down to less than the Compton wavelength. Q-1 dynamics therefore always remain operative.

[18]But not space itself, which remains perfectly real and meaningful.

[19]Pilot wave theory may provide deeper insight on the Born Rule, but it cannot answer the general question of natural computation.

[20]The term *micro-measurement* henceforth signifies measurement-like processes that specifically fall under Q-2.

3.2 Uncertainty Principle

Q-2 provides several perspectives on the uncertainty principles.

The uncertainty principle of the first kind, involving pairs of mutually complementary dynamic attributes (*e.g.*, position and momentum) can be thought of as arising from a continual interplay between Q-1 and Q-2 dynamics. The former tends to expand the wave-like spread of the W-state and thus to increase the uncertainty product. The latter, on the other hand, tends to narrow the W-state and keep it from straying far from a concentrated classical particle-like form; that tends to decrease the uncertainty product. The interplay is the essence of *continuous spontaneous locationization* (CSL) in GRW-like theories.

This view of the uncertainty principle differs significantly from that of conventional quantum theory, wherein the lower bound on the uncertainty product is derived from the Fourier decomposition of the wavepacket and is thus explained entirely within Q-1. In the new framework, by contrast, it arises from the joint dynamism of Q-1 and Q-2.

Decoherence is a consequence of the cumulative effects of micro-measurement processes, which ubiquitously buffet all quantum systems. It keeps quantum interference effects – and the entire scope of Q-1 – limited to small scale in microscopic[21] systems. It follows that Nature, in effect, places a soft upper bound, as well as a hard lower bound, on the uncertainty product.

The energy-time uncertainty principle is qualitatively different from the first kind. It essentially establishes narrow time windows over which unusual forms of W-state behavior arising from micro-measurement fluctuations can persist before being decohered out of existence.

3.3 Wavepacket Expansion

For the dynamics a free particle, CSL and conventional quantum theory paint very different pictures of W-state evolution[22]. The latter picture is that of a Gaussian wavepacket whose width grows over time. As was argued in the previous paper [11], that seems odd and not right in several respects. CSL, by contrast, implies a wavepacket whose width remains more or less constant over time, but whose center executes a random walk.

The random walk arguably seems, subjectively, like a more realistic and credible depiction of dynamics in the microworld. Q-1 by itself, without Q-2, simply does not feel right. It not only leads to the absurdity of the cat, but it also seems just too static[23].

3.4 Time-Dependent Perturbation Theory

Traditional quantum theory is remiss most sorely in that it fails to pinpoint measurement events, except at points of last resort where the buck stops with a conscious observer. As a result, too much scope and authority is conferred to the unitary Rule 1 formalism. The oddity of wavepacket expansion is a symptom of its overextension.

Time-dependent perturbation theory (TDPT) poses a much more serious host of inadequacies in conventional quantum theory stemming from the overextended scope of Rule 1. TDPT is a staple tool of the trade that is routinely applied by practitioners and taught in all quantum physics courses and textbooks. It was at the heart of the remarkably great run that quantum mechanics has enjoyed for most of the past century. However, it is internally contradictory.

On the one hand, the mathematical formalism of TDPT is couched entirely in terms of Rule 1, and the resulting solution of the Schrödinger equation is ostensibly an uncollapsed wavefunction. However, the pragmatic quest is to derive transition rates as probabilities per unit time. The Fermi Golden Rule provides those, but it does so by applying the Born Rule to the uncollapsed wavefunction. TDPT strives to be Rule 1 only, but it is forced to invoke Rule 2 in expedient fashion.

TDPT serves the purpose of providing a transition rate formula that proves empirically accurate and useful, but that is it. TDPT cannot go any further because it provides no account of what transitions are or how they transpire in individual systems. Indeed, the conventional framework is evasive on the basic question of whether any irreversible bifurcation takes place. Furthermore, it blatantly ignores the Copenhagen requirement of observer intervention to trigger Rule 2 (*e.g.*, in spontaneous emission, when nobody is looking at the atom).

[21] In mesoscopic systems too, in rarefied cases.

[22] Odd, as one would think that a free particle should be the simplest and most conclusively solved of all textbook problems!

[23] In quantum pedagogy, this is no less conceptually troubling than any of the strangeness in the two-slit experiment.

3.5 Pinpointing Measurement Events

With the integration of Q-2, the realist framework maintains that physical wavefunction collapse is the only way to recognize and treat micro-measurements properly for what they are. However, they must be approached with caution. This is the infinite regress issue.

In pinpointing measurement processes, it is easier to prove a negative (*i.e.*, to say when a measurement process has *not* occurred) than to prove a positive. The former applies when a quanton is split into two or more subsystems, which can be recombined in a way that undoes the split. One simple example is the splitting of a photon beam. Although the insertion of the beam splitter into the path of a photon, at first glance, seems like a potentially disruptive intervention, the beam-splitting itself definitely does not qualify as a measurement process, since the daughter beams (half-photons) can be recombined without loss of the original phase relationships or beam directionality.

A second example is a Stern-Gerlach (SG) magnet. Suppose that a silver atom, whose spin is horizontally aligned (for concreteness, spin-right), encounters a vertically aligned splitter. The daughter beams will be spin-up and spin-down, but they can be recombined to restore the original spin-right state. Hence, the splitting does not qualify as a measurement process, and the spin-right state can be said to be a superposition of spin-up and spin-down in an operationally meaningful sense.

The upshot is that a splitting process can be determined *not* to qualify as a measurement process if the resulting subsystems (separated wavefunction branches) constitute components of a superposition. That means that the subsystems bear strong phase relationships with one another, such that they can be recombined in an interesting way (*e.g.*, restoring the original spin alignment in the SG example).

3.6 Superposition

Superposition has two meanings in the realist framework. It is a local property of the W-state, but it also applies to whole quantum systems of one or more quantons.

How can superposition, in the latter sense, be defined operationally? Can a radioactive nucleus be considered a superposition of decayed and undecayed states? To answer in the affirmative, there would have to exist, at least in principle, a means of spatially separating the states and recombining them to restore the original state, as it existed before the divergence began. That would mean, for example, separating the live-cat and dead-cat states and combining them to restore what is undoubtably the live cat, as it was before being placed into the box. Some application examples, such as the photon beam splitter and SG magnet, can readily satisfy this operational criterion, but the cat and the nucleus almost certainly cannot. It follows that the development of Q-2, as a physical theory, should model radioactive decay as an irreversible bifurcation process that takes place in individual nuclei.

3.7 Decoherence

There is more to the measurement problem than the core part that has been addressed. It additionally includes the general question of why superpositions almost never arise in large systems with more than a few quantons.

In mainstream approaches, decoherence is couched entirely in terms of Q-1, and significant insights have been forthcoming. If a mesoscopic, initially prepared in a well-ordered W-state configuration, is brought into contact with macroscopic surroundings, the order is quickly destroyed because of phase randomization in the entangled union of systems.

The realist framework holds that micro-measurements and Q-1 dynamics both drive decoherence. That is, decoherence arises from outright cessation of unitary evolution as well as phase randomization effects. Q-2 dynamics imply that decoherence occurs even in perfectly isolated quantum systems and thus becomes a matter of fundamental limitations, rather than the practical impossibility of staving off interactions with surroundings once quantum systems exceed some critical size.

3.8 Action Integrals

An upshot of Q-2 is that Q-1 - and therefore the determinism that goes with it - is fundamentally truncated in scope. It follows that in the formalism purely of Q-1, it is rigorously correct to speak only of short threads regarding world line trajectories and action integrals.

Q-2 provides a new perspective on Feynman path integrals, which were addressed in the previous paper [11]. They countenance the notion of action integrals defined on arbitrary world lines between two given points, and thus phase relationships between arbitrary points on different rest manifolds. However, they raise the question of why multiple arbitrary paths (as opposed to just the one classical path) would meaningfully exist in the first place and contribute to an overall action integral.

If micro-measurements were nonexistent, there would normally be just one thread that intersects any two time-like separated points, just as in classical mechanics. Amidst micro-measurements, however, threads are continually shattered and rearranged. It is still meaningful, both for individual systems and ensembles, to speak of an action integral along an arbitrary path, but it can be calculated only by dividing the path into a sequence of waypoints and short interconnecting segments. Q-1 can be used to compute action increments along the short segments, whereas Q-2 is needed to traverse the waypoints. The latter requires accounting for phase shifts and amplitude ratios between the local W-states on the both sides of a rest manifold.

With the ability to compute path integrals, the W-state dynamics, driven by both Q-1 and Q-2, become formulated in terms of Green's functions, which are akin to Huygen's Principle. The mathematical approach was detailed in the previous paper [11].

3.9 Entanglement as a Dynamic Process

Conventional discourse frequently speaks of quantum systems *becoming* entangled by virtue of their becoming close to one another and interacting. They then remain entangled, even after becoming physically separated, until one of them is subjected to a measurement process.

That implies that entanglement is an irreversible dynamic process. Conventional quantum theory implies that it takes place entirely under Rule 1, but that raises the question of how it can be irreversible, given that the Schrödinger equation has time reversal symmetry.

The new framework maintains that Q-2 plays an essential role in the dynamic process by breaking the time reversal symmetry. It produces an arrow of time, which is now integrally built into the core structure of quantum theory.

4 Q-2 and Q-3: Physics of Quantum Measurement

Q-2 encompasses measurement processes that are internally triggered. They occur even in systems perfectly isolated from surrounding environments. They are either of completely spontaneous origin (reifying the notion of quantum fluctuations) or arise from instability within a system (*e.g.*, as in an excited atomic electron or a radioactive nucleus).

Q-3, by contrast, encompasses measurement processes that are externally triggered. They arise when one quantum system comes into contact with another system (of any size). Experimental interventions, the central focus of traditional quantum theory, are a subset of processes of this type.

4.1 Specification of Measurement Process Type

From a practical perspective of analysis, there are at least two important differences between internally and externally-triggered measurement processes. One is that the former occur ubiquitously and must therefore be treated by statistical methods. The latter, at least in well-controlled experimental settings, generally occur infrequently and can be treated as discrete events.

A second difference is that for externally triggered processes, the type of measurement must be specified. In a measurement process, the interaction that takes place between a quantum system and the measuring device is non-conservative in that it cannot be represented by a Lagrangian function. Moreover, unlike in classical mechanics, the interaction cannot be quantified at all in terms of a force law. Instead, it can only be represented abstractly as U, which denotes the interaction with the environment locally at some point. The quantitative character of U is left vague. In standard quantum theory (and in the new framework), U translates to a set of projection operators that map Hilbert space vectors (*i.e.*, snapshots of W-state on a rest manifold) to the eigenspaces of the dynamic attribute being measured.

4.2 Holistic Character of Quantum Measurement

It was noted that P-state has the distinctly non-classical property of not being localized; it exists only globally on a rest manifold as a whole. The same is true of U, but only as a simplification for describing the application of a traditional measurement process to a quantum system. In the simplified model, the measurement is assumed to occur at a single instant of proper time (*i.e.*, on a single rest manifold). U then expresses the type of measurement process to which the system as a whole is being subjected. In this respect, it represents the holistic experimental setting envisaged by Bohr.

5 Q-4: Quantum Gravity

Quantum gravity is built as a fourth tier (Q-4) atop the tri-partite foundation. The recommended approach is to gravitize quantum theory, based on the new realist framework.

5.1 Constants of Fundamental Physics

Quantum gravity contains three fundamental constants: G (gravitational constant), $\hbar$ (Planck's constant), and c (speed of light). Each of these represents the centerpiece of a theory of principle[24]:

- $\boldsymbol{c}$: The speed of light (c) originates in special relativity.
- $\boldsymbol{G}$: The gravitational constant (G) originates in general relativity.
- $\boldsymbol{\hbar}$: Planck's constant ($\hbar$) originates in quantum theory.

The enterprise of theoretical physics can be thought of as a box with three knobs corresponding to the fundamental constants. Physics plays out by plugging constitutive theories[25] into the box. In this view, the fundamental constants are taken for granted as such and regarded as adjustable hyperparameters, both in the theories of principle and the constitutive theories that depend on them. The framework does not address questions of whether the fundamental constants can be explained more deeply.

5.2 Matrix of Regimes of Fundamental Physics

Relativistic quantum gravity (RQG) signifies the ideal of a comprehensive theory of principle that incorporates all three fundamental constants. It can be regarded as the pinnacle of a framework in which fundamental physics is represented as a matrix (cube) of physical regimes, defined by combinations of the asymptotic limits: $G = 0$, $\hbar = 0$, $c = \infty$.

The matrix yields a set of eight regimes, which are indexed as rows of a truth table. Each regime in the cube is notionally encoded by three bits, respectively representing $G > 0$, $\hbar > 0$, and $c < \infty$.

$G = 0$ is interpreted to mean not the complete absence of gravity but the limit of weak gravitation, such that the space-time backdrop differs negligibly little from flat.

Regime 0: $\boldsymbol{G = 0}$, $\boldsymbol{\hbar = 0}$, $\boldsymbol{c = \infty}$

This is the regime of non-relativistic classical physics. Newtonian gravitation is included in regime 0, but technically as a constitutive theory. It is considered *phenomenological* insofar as it has experimental justification (*e.g.*, the work of Galileo and Cavendish, which long predates Einstein), but it is also considered *ad hoc* in that it lacks any deep theoretical justification at this level. Regime 4 explicitly recognizes Newtonian gravitation as the non-relativistic limit of general relativity and the equivalence principle as rooted in gravitation as geometry, but Regime 0 is officially ignorant of that insight.

Regime 0 additionally admits numerous subdisciplines of conventional physics and engineering that do not rely on theoretical insight from the higher regimes. Examples include classical thermodynamics, which can be accepted as a purely phenomenological theory of the macroscopic realm, and electrical network theory, which leverages electromagnetic theory at only a rudimentary level.

[24] A physical *theory of principle* is one that describes a facet of the "fabric of reality". It is universal in nature and scope.

[25] A *constitutive theory* introduces specialized physical content atop a theory of principle. That content is "optional" in that Nature could notionally exist with or without it.

Table 1: Matrix of Regimes of Fundamental Physics

Regime Number	$G > 0$	$\hbar > 0$	$c < \infty$	Brief Description
0	0	0	0	Classical mechanics
1	0	0	1	Special relativity, classical electromagnetism
2	0	1	0	Non-relativistic quantum theory
3	0	1	1	Relativistic quantum theory
4	1	0	0	Classical mechanics with Newtonian gravitation
5	1	0	1	General relativity
6	1	1	0	Non-relativistic quantum gravity
7	1	1	1	Relativistic quantum gravity

Regime 1: $G = 0$, $\hbar = 0$, $c < \infty$

This is the classical regime that encompasses special relativity and electromagnetism. It accounts for all non-quantum phenomena in which the finiteness of c figures importantly and gravitation is weak.

Classical electromagnetism is a constitutive theory, but because it is so omnipresent and centrally important to physics, it is the *de facto* mission of this regime to do full justice to it. Its only limitation is that although it introduces the vector potential $(\boldsymbol{A}, \phi/c)$ and recognizes its practical usefulness, it is unable to explain its deeper significance, such as manifest in the Aharonov-Bohm effect.

Regime 2: $G = 0$, $\hbar > 0$, $c = \infty$

This is the regime of non-relativistic quantum theory. It encompasses the Schrödinger equation and the Bohr model of the hydrogen atom. It aligns with historical development and is the level at which most introductory textbook coverage of quantum mechanics is pitched.

Technically, c does not enter non-relativistic quantum mechanics directly, but only through the fine structure constant, *viz.*,

$$\alpha \equiv \frac{e^2}{4\pi\epsilon_0\hbar c} \approx \frac{1}{137} \tag{2}$$

In this regime, α is regarded as a hyperparameter whose value is arbitrary but accepted at face value. No attempt is made to fathom its value or tantalizing nature at a deeper level.

It is noted that because it depends on the electron charge, e, and electromagnetism is a constitutive theory, α is not considered a constant of nature with the same fundamental stature as G, $\hbar$, or c. Tuning of α, as a hyperparameter, is notionally effected through tuning of e, not $\hbar$ or c.

Regime 3: $G = 0$, $\hbar > 0$, $c < \infty$

This is relativistic quantum theory in the limit of weak gravitation. In practical terms, it represents the widest range of physics practice and covers the exact same ground as the tri-partite foundation of the new framework. It encompasses the Dirac theory of the hydrogen atom, quantum electrodynamics (QED), all of atomic and nuclear physics, quantum chromodynamics (QCD), and the Standard Model of particle physics.

Regime 4: $G > 0$, $\hbar = 0$, $c = \infty$

This is the non-relativistic limit of general relativity, in which all relevant speeds are small compared to the speed of light. It is of interest primarily as (*i*) a practical simplifying approximation of general relativity, and (*ii*) a bridge between general relativity and classical celestial mechanics.

Regime 5: $G > 0$, $\hbar = 0$, $c < \infty$

This is general relativity. In occupying this niche in the framework, general relativity represents the pinnacle of classical physics. It says all that there is to say about Nature under conditions where the non-zeroness of $\hbar$ is unimportant.

Regime 6: $G > 0$, $\hbar > 0$, $c = \infty$

This is the regime of non-relativistic quantum gravity, which signifies domains of phenomena in which G and $\hbar$ both figure importantly, but c does not.

This regime is the only unfamiliar one in the cube, and it might well be nothing more than a curio. Whether it might realistically exist at all in the first place, actually describes any phenomena occurring in any regions of cosmic space-time, or might be accessible to observation are open questions.

Regime 7: $G > 0$, $\hbar > 0$, $c < \infty$

This signifies RQG, which is the most general case, in which all three constants are in play. It is the stage on which the fabled "theory of everything" (TOE) would play out. This regime represents the holy grail of theoretical physics.

5.3 Relationships between Regimes

- *Quantization* signifies the generalization of a classical regime to the corresponding quantum regime. The latter differs from the former only in the $\hbar > 0$ bit. For example, regime 3 (relativistic quantum theory) is the quantization of regime 1 (classical physics without general relativity). Attempts to develop quantum gravity starting from general relativity (*i.e.*, going from regime 5 to regime 7) also represent quantization.

- *Gravitization* signifies the generalization of a flat regime (*i.e.*, with a flat space-time backdrop). The latter differs from the former only in the $G > 0$ bit. Gravitization of the quantum (*i.e.*, going from regime 3 to regime 7) is the approach to quantum gravity recommended in this paper.

- *Relativization* signifies the generalization of a non-relativistic theory. Most simply and historically first, regime 1 (relativistic classical mechanics) is the relativization of regime 0.

5.4 Background Independence

In the realist framework, the energy-momentum tensor of general relativity can be derived from the W-state within the formalism of Q-1. The next step is to show that the non-gravitized baseline quantum theory (*i.e.*, Q-1, Q-2, Q-3) rests atop a space-time backdrop that is flexible, *i.e.*, can accommodate gravitational distortions arising from great concentrations of energy-momentum.

The realist framework is well-designed to be background-independent. Whereas conventional quantum theory is built on absolute time and a fixed background, the realist framework is fundamentally reliant only on quanton proper time, which is dynamic in nature and flexible.

5.5 Non-Linearity

A second problem that quantum gravity must solve is how to square quantum theory, which is linear, with general relativity, which is nonlinear.

The realist framework distinguishes local superposition, which applies to local W-state, with superpositions of whole-quanton states. Local superposition will continue to hold and remain linear, since the local reality of W-state will not change under gravitization. However, whole-quanton states, for quantons in strong gravitational fields, will no longer combine linearly.

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

[11] E. Larson. "A New Foundation for Standard Quantum Theory". In: *viXra e-prints* (2024). viXra: 2402.0149.

[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.