

Quantum Foundations, Quantum Gravity, and Origin of Inertia: A Definitive New Realist Framework

Edward C. Larson
eclars1071@gmail.com

Abstract

This volume presents a comprehensive realist framework encompassing quantum foundations, quantum gravity, and the origin of inertia (Mach's Principle). It develops and builds upon a quantum ontology consisting of two fundamental ontic 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 enforces entanglement obligations and mediates the global coordination within quantum systems required to bring about wavefunction collapse in causal fashion consistent with special relativity.

Quantum theory is rebuilt from the ground up, and the development then proceeds to quantum gravity, which is solved surprisingly easily once a good quantum foundations solution is in hand. It is solved not in the Planck regime, but in the testable regime of classical general relativity. The two great theories are intermeshed, and proposed testable solutions for the dark matter conundrum and origin of inertia are set forth. Both depend on non-local gravitational sourcing via P-state. The overall result is a robust architectural foundation for a (still elusive) Theory of Everything.

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1 Introduction

This volume is structured as a Trilogy, which encompasses and presents solutions for three key foundational topics at the core of fundamental physics: (i) quantum foundations, (ii) quantum gravity, and (iii) the origin of inertia (Mach's Principle). It thus provides an *architectural foundation* for a (still elusive) Theory of Everything (TOE_f).

1.1 Quantum Foundations Preview

Quantum foundations (QF) is the most basic and important of the key foundational topics. The top priority of theoretical physics, it is the very first problem that must be solved definitively for once and for all.

1.1.1 Realist Quantum Framework

The QF solution presented in the Trilogy is a novel *realist quantum framework* (RQF). It is based axiomatically on a dual ontology, which, at the highest level of summarization, consists of:

- **W-state:** wave-like, local, physical state, embodying the physicality of matter-energy;
- **P-state:** particle-like, global, informational state, mediating entanglement effects and particle holism.

It also posits, in the axiomatic foundation, dual dynamics based on fundamental dichotomous distinction between:

- **Rule 1:** Smooth deterministic unitary evolution of W-state, akin to the Schrödinger equation;
- **Rule 2:** Wavefunction narrowing (not wholesale collapse), governed by the Born Rule.

1.1.2 Importance of Quantum Foundations

Why is QF important?

- QF is, above all, about making the core subject matter at the heart and forefront of modern science intelligible. It has not been that for the last 125 years, because of foundational disarray stemming from the conceptual intractability of quantum physics. It is only from a 21st-century vantage point, with a full century of hindsight and progress, that light at the end of a 125-year-long tunnel starts to become visible.
- Foundational disarray in quantum theory unfailingly breeds confusion, narrative failure, and muddled pedagogy and practice. That much becomes instantly apparent to students early on in most any quantum course - introductory or advanced. Just about every topic, as it is customarily portrayed and presented in textbooks, is riddled with contradictory or misleading explanation that inevitably sows deep puzzlement. Mathematical elegance - and even predictive utility - of the mathematical formalism is ultimately beside the point, when clear and comprehensible connection to the underlying physics is lacking.
- In human terms, the price of foundational disarray, paid by those who take up physics professionally for a living, is career-long cognitive dissonance. No matter how it is spun, that belies the unvarnished sense of curiosity that motivates most people to take up the study of science in the first place.
- Quantum physics being so central, fundamental, and universal in scope, QF must be solved before headway on the other two foundational topics can be achieved. Without solution, fundamental physics and investigation of the deepest puzzles of astronomy and cosmology are doomed to run on fumes. Despite a remarkably good run that quantum mechanics had during the middle decades of the last century, they have arguably been doing so since the 1940's.
- The challenge of QF is not only technical (*i.e.*, overcoming the hard issues that have made it conceptually intractable); it is also about prevailing over powerful historical prejudices. For QF, that substantially includes anti-philosophical instrumentalist dogma, which holds that QF is not legitimate science. Nothing could be further from the truth.

1.1.3 Realism

The RQF is a fully relativistic all-new construction of quantum theory from the ground up. To claim that the framework is realist conveys two principal points:

- **Formal transparency:** All elements and constructs introduced and developed in the theoretical formalism clearly and unambiguously correspond to and represent physical reality (*i.e.*, W-state, P-state, space-time).
- **Narrative clarity:** The theory is capable of telling a straightforward account of what Nature is like and how it behaves. That means being able to answer basic story-telling questions of what, where, when, and how.

As a technical endeavor, QF is the quest for a viable realist replacement of conventional quantum theory. Any definitive QF resolution, almost as a tautology, must necessarily be realist. Nothing short of a full-fledged realist quantum theory can satisfactorily address the preceding points.

In practice, realism is frequently construed to signify a narrowly technical stance. It is said to hold that quantum systems are “ordinary objects”, measurement processes acting upon which passively reveal pre-existing attribute values. That is not at all what realism in the RQF means. It is perfectly tenable for realist theories to speak of quantum systems whose dynamic attributes (W-state) are in objectively real states of indefiniteness.

1.2 Quantum Gravity Overview

The second part of the Trilogy turns attention to quantum gravity, once the RQF solution has been developed. Quantum gravity (QG) is a uniquely important problem in its own right because it is about unifying the two most important theories of principle in physics. Quantum theory (QT) and general relativity (GR) both describe the very fabric of physical reality and are universal in scope. They must therefore somehow intermesh.

1.2.1 Regimes of General Relativity

GR spans five (5) regimes, which occupy a spectrum based on strength of gravitation:

- **Regime 1: Newtonian gravitation.** In this regime, gravitation is sufficiently weak that the departure from strictly flat Euclidean backdrop is negligible. Quantum physics, constructed anew in the RQF, can exist self-contained on its own without gravity. W-state in Regime 1 derives entirely from the constitution of matter-energy constructible from the inventory of elementary quanton types recognized in the Standard Model.
- **Regime 2: Linear approximation of GR.** This is the regime of moderate gravitation, which encompasses effects observable in the solar system, including (*i*) Mercury perihelion precession, (*ii*) bending of starlight around the sun (as in the Eddington eclipse observations), (*iii*) gravitational time dilation, and (*iv*) Lense-Thirring gravitational effect of rotating mass. The principal task of QG in Regime 2 is to explain and model the origin of gravitation from the RQF theory of matter-energy. The source of the gravitational field is the energy-momentum tensor, $T_{\mu\nu}$, in the Einstein-Hilbert field equations. In Regime 2, $T_{\mu\nu}$ originates exclusively from W-state in Regime 1.
- **Regime 3: Nonlinear GR.** This is the regime of strong gravitation, such that nonlinearity becomes important. The task of QG in Regime 3 is two-fold: (*i*) Additively combining the quantum contribution of the Regime 1 W-state to $T_{\mu\nu}$ with that of the Regime 2 gravitational field. Additive combination continues, of course, with feedback of higher-order gravitational contributions to $T_{\mu\nu}$. (*ii*) Ensuring that QG implements the *general invariance* criterion of classical GR. This is the crucial architectural feature that makes the full nonlinear theory of gravitation self-constructing, from an elegant minimum of foundational axioms.
- **Regime 4: Ultra-strong gravity.** This regime, in practice, focuses specifically on black hole and gravitational wave phenomenology. It is where GR makes its most spectacular and stunning predictions and where observational astronomy is richest. Regime 4 is where the full Einstein-Hilbert field equations and Schwarzschild analysis become paramount and where GR nears the singularity limit.

- **Regime 5: Planck extreme.** This is the final backstop, which is a bulwark that staves off physical singularity. Characterized by the stupendously tiny Planck length, L_P , this is where gravitational distortion is so strong that the global hyperbolicity of rest manifolds (*i.e.*, foliation structure emergent from W-state) ceases to hold, and the P-state is no longer able to perform its mediating role. The RQF-based QG solution framework is self-aware of its own scope limitation.

1.2.2 Locus of Unification

A surprising result of the QG analysis, with the Regime 1 RQF solution in hand, is that the locus of unification between the two great theories is in Regimes 2-3. A synopsis:

- The Planck mass, M_P , which is of modestly macroscopic magnitude, is decisively important. It represents the smallest aggregation of matter-energy that can effectively gravitate.
- QG in Regime 2 provides fundamental explanation for the *origin of gravitation* from the microscopic constituents of matter-energy (*i.e.*, W-state in Regime 1). Moreover, P-state furnishes a crucial mechanism through which gravitation can be sourced non-locally (*e.g.*, a widely dispersed quorum of microscopic masses).
- The Planck mass marks a transition zone, across which the “quantumness” (which goes by the technical term *multi-situationality*) characteristic of W-state in Regime 1 decoheres into the classicality (*uni-situationality*) that uniquely characterizes gravitational fields and their self-energy.
- The decoherence from multi- to uni-situational W-state that straddles the transition zone is extremely fast. The time constant is the stupendously tiny Planck time, T_P , meaning that the decoherence is for all practical purposes instantaneous.

1.2.3 Odd-Couple Opposites

The QG analysis shows that the two great theories, for the most part, remain odd-couple opposites and continue to occupy almost mutually exclusive regimes. QT dominates in the microdomain (Regime 1), whereas GR reigns nearly exclusively in Regimes 2-4, where it remains virtually identical to the classical theory. The transition zone between the quantum and classical domains in Regime 2 is very thin (*i.e.*, characterized by virtually instantaneous decoherence) but nevertheless seamless.

Prevailing sentiment traditionally has held that GR will have to acquiesce to quantum mechanics (QM), because the latter has been the golden child of physics that has never been proved wrong (across a much wider range of phenomenology than GR). The QG analysis, supported by the RQF, reveals the opposite: GR is on stronger ground because, as a classical theory, it is ontologically unambiguous, whereas conventional QT, which has guided all prior QG efforts and programs to date, is plagued by foundational issues.

The RQF makes the fusion in Regimes 2-3 remarkably easy. The fusion becomes feasible and tractable because the RQF is a much more classical *kind* of theory than traditional QM. It retains the mathematical machinery and visualizable imagery of classical mechanics and electromagnetism, integrates it with the distinctively non-classical elements of the new quantum ontology, and incorporates it as the engine under the hood that powers the W-state dynamics.

1.2.4 Historic Focus on the Planck Regime

The realist QG solution framework puts the three Planck units in their rightful places. The Planck mass, M_P , and Regimes 2-3 are well within experimentally testable reach. The time, T_P , and length, L_P , units, on the other hand, are demonstrably theoretical curios. T_P surfaces only as a stupendously tiny decoherence time constant, and L_P surfaces only in Regime 5, well inside event horizons. “Theoretical curio” is not merely a philosophical assessment; it is provable, within the QG solution framework, that it is impossible to probe either experimentally using equipment constructible from Regime 1 W-state.

That the locus of unification is in Regimes 2-3 is radically different from conventional anticipation, which focuses almost exclusively on Regime 5. String theory and loop quantum gravity are both invested deeply in the premise that Regime 5 not only will be the locus of unification for QG, but also that it holds the keys to the

kingdom for all future progress in fathoming the ontology of Nature (*e.g.*, highly-dimensional string topologies) at the most microscopic level and in explaining the Standard Model more deeply.

The realist QG solution framework has no need for - and, in fact, is fundamentally incompatible with - supersymmetry (SUSY). The RQF, by design, accommodates sharp dichotomies in the structure and dynamism of quantum physics (*e.g.*, W- and P-state, Rule 1 and Rule 2, fermions and bosons), whereas mainstream approaches heavily favor premises of overarching symmetry. SUSY, and by implication also string theory, thus lock themselves into specific positions on QF.

1.3 Origin of Inertia Overview

1.3.1 Fact of Inertia

The RQF, combined with the QG solution, almost amounts to a TOE_f for the observable universe and the full dynamic range of accessible scales, from quarks up. QG technically falls short of cosmological scope (as it should).

The “almost” is due to one important feature of Nature that the RQF and QG together cannot explain: the *fact of inertia*. First recognized and articulated by Galileo, FoI is one of the deepest foundational mysteries of physics. The origin of inertia is to cosmology what QF is to quantum physics.

How is it that we can feel ourselves accelerating or spinning when we close our eyes? Local distributions of matter, within our terrestrial confines, are unable to supply answers. It dawned on Mach that it must somehow have to do with the large-scale distribution of matter in the cosmos, but his dogmatic positivism ironically double-crossed the investigation of his own Principle.

1.3.2 Formalization of Mach’s Principle

Mach’s Principle has often been denigrated and dismissed as unscientific and untestable. Untestable? Possibly, for the simple reason that no experiment can be shielded from gravity. Unscientific? No. Not if it can be pitched as a well-posed set of questions within the combined framework of the RQF and QG.

The Machian dynamics problem is formulated in a spherical coordinate system, with $r = 0$ at our terrestrial location. There exists at $r = 0$ a small mechanical system, notionally Newton’s bucket, well-isolated from all terrestrial surroundings. The rest of the universe (RotU) is a spherically symmetric shell of mass density $\rho(r)$, which is appreciably non-zero out to extremely large r (approximating the radius of the universe). The spherical symmetry is justified by the empirical fact that the universe looks the same in all directions. The mechanical problem is analyzed in the framework of relational mechanics, which requires:

- The center of mass of the bucket and RotU is fixed at $r = 0$.
- The net rotational momentum of the bucket and RotU is zero.

We accept those as reasonable Machian constraints, but not the more questionable criterion of a net zero-energy universe. We consider two problem scenarios, which are straightforward to analyze using familiar methods in the Newtonian framework of absolute space-time:

- **Translational Acceleration:** The bucket is initialized force-free at rest or some constant velocity. According to Newton’s laws in the terrestrial setting, it should feel no acceleration. But suppose that the RotU accelerates by just a small amount, equal to what would be a moderate translational acceleration for the bucket. The bucket and RotU interact only through long-range gravitation at cosmic scale. Can the QG framework tell us whether the bucket feels an acceleration?
- **Rotational Velocity:** The bucket is initialized with rotational velocity zero. According to Newton’s laws in the terrestrial setting, the water should stay flat. But suppose that the RotU rotates by just a small amount, equal to what would be a moderate rotational momentum for the bucket. Can the QG framework tell us whether the water in bucket goes concave?

1.3.3 Machian Dynamics Findings

Classical GR predicts modest Machian effects, owing to frame dragging in the translational scenario and Lense-Thirring in the rotational scenario. It is generally doubtful, however, whether those mechanisms are strong enough to resolve Mach's Principle conclusively. The Lense-Thirring effect can account for the water concavity only under the assumption of an improperly divergent mass integral of $\rho(r)$ out to $r \rightarrow \infty$, implying reliance on open universe models.

The QG solution, on the other hand, supports much stronger W-state coupling between the bucket and the RotU. It predicts that the bucket indeed feels an acceleration in the translational scenario. Inertia is the local resistance to departure of the W-state of the bucket from free fall, the geodesics defining which are ultimately determined by gravitation, writ large globally across the cosmos. P-state acts as a Noetherian ledger that enforces conservation of total momentum globally across the cosmos. The non-local mediation mechanism, which is at the theoretical minimum of the RQF, ensures that any local acceleration of the bucket is immediately tallied against the W-state of the RotU to maintain net zero translational momentum globally. The inertial mass of the bucket is thus a measure of coupling strength between the W-states of bucket and RotU. This is the *origin of inertia*.

In the rotational scenario, non-local coupling between the rotational momenta of the bucket and RotU imparts concavity to the water much more strongly than Lense-Thirring. The QG analysis confirms that any local rotation of the bucket is immediately tallied against the W-state of the RotU to maintain net zero rotational momentum globally. The rotational momentum of the RotU is the reification of Newton's absolute space. The conditions on $\rho(r)$ become far less restrictive, potentially reviving consideration of closed universe models.

1.3.4 Quantum Cosmology

It is a remarkable result that classical GR is insufficient to resolve Mach's Principle; it takes a quantum solution to mediate non-local cosmic gravitation. This, in and of itself, makes quantum cosmology a serious subject, with big catches to its name!

The quantum cosmology of the 1960's, pioneered by Wheeler and DeWitt, was far too premature and ahead of its time - almost anachronistically so. It was ultimately doomed to fail, because unlike the TOE_f, it was not supported by QF or QG solution prerequisites. Furthermore, their work was guided by the faulty premise of Rule 1 primacy.

The two great theories remain odd-couple opposites, in their separate regimes, in the sense that there are few testable settings in which \hbar and G both figure importantly in the local W-state physics. The quantumness of quantum cosmology instead lies in P-state mediation at cosmic scale.

P-state mediation of cosmic gravitation reifies Newton's original worry about spooky action at a distance. For a time more than a century ago, it seemed that the classical relativistic field theories of electromagnetism (Maxwell) and gravitation (Einstein) dispelled non-locality concerns, as interactions were thence thought to be mediated via local interactions between matter and fields. Non-local entanglement phenomenology in QT reverses that dismissal of concern. It also reinstates the Newtonian concept of global time.

1.4 Testable Hypothesis: Solution of the Dark Matter Conundrum

1.4.1 Dark Matter Hypothesis

The TOE_f offers a testable hypothesis, which holds that the dark matter (DM) conundrum - one of the deepest mysteries of astronomy - can be resolved without need for new types of particles. The key principle supporting the hypothesis is that long-range gravitational influence at the galactic fringe is determined by the non-local tally, by the galaxy-wide P-state, of W-state energy and rotational momentum at the galactic core, not by local density at the fringe.

The DM conundrum is the discrepancy between observed gravitational effects (*e.g.*, galactic rotation curves, cosmic web clustering) and expectation based on visible mass at the fringe. The quantum cosmology insights suggest that the missing gravitational influence is caused not by unseen local mass (conventionally thought to require supposition of exotic new types of particles), but instead by how the galaxy-wide P-state mandate (*i.e.*, conservation of galaxy-wide rotational momentum) plays out at the galactic fringe. The high stellar velocities at

the fringe are determined primarily by energy and momentum concentration at the galactic core, whose gravitational influence extends much further than predicted by classical theory. The non-local effect of P-state obviates supposition of unseen gravitating mass and exotic new types of particles to account for its constitution.

1.4.2 Observable Effects

The non-local P-state mandate produces two key observable effects:

- **Strength:** The gravitational field is much stronger than expected far from the galactic core, supplying what is equivalent to the mass deficit.
- **Directionality:** The gravitational field is highly spherical and isotropic, producing a DM “halo”, because the P-state’s non-local summation averages out local anisotropies, creating smooth long-range gravitational pull.

The direct observable consequence of the P-state’s non-local work is the flat rotation curve of spiral galaxies, which is the principal evidence of DM phenomenology. Newtonian expectation holds that star velocity (v) should be inversely related to distance (r) from the center, *viz.*, $v \propto r^{-1/2}$. The observational evidence, however, clearly indicates flat rotational curves, *i.e.*, that v is essentially constant (independent of r). The QG explanation is that the P-state enforces a galaxy-wide field configuration that produces the high stellar velocities at the fringe.

The available observational evidence provides an independent quantitative means of performing a “head count” on the mass quorum sourceable from the galactic core. It can be done indirectly based on: (*i*) the magnitude of the flat velocity profile of stars far from the galactic center, and (*ii*) gravitational lensing of light emanating from the core and working its way past the DM halo.

1.4.3 Falsification Challenge

The TOE_f makes a specific testable claim about the source of the missing gravitational influence. It predicts that the total mass required to generate the observed velocities at the fringe is precisely equal to the amount of visible W-state mass near the galactic core that the P-state’s non-local tallying mechanism is aggregating. It must calculate what amounts to a QG transfer function, which mathematically describes how the P-state extends the influence of the centralized mass (W-state). This function is determined by the W-state (*i.e.*, a galaxy model) and the resulting geometry of the rest manifold, as it cuts through the galaxy. It can then be used to predict the amount of extra gravity at the fringe. The calculation must proceed from the premise that the W-state at the core arises entirely from the known inventory of quanton types in the Standard Model.

1.4.4 Implications of Hypothesis Vindication

If the calculation quantitatively predicts the fringe velocities (or, equivalently, the mass deficit) correctly, it would have at least three major implications:

- It would amount to an elegant and parsimonious resolution of the DM conundrum, obviating supposition of an extra particle inventory and the elaborate theoretical machinery (*e.g.*, SUSY, string theory, WIMP’s, axions) to support it.
- It would strengthen the case that the Standard Model, as it stands, is a complete inventory of quanton types from which all W-state in the observable universe is constructible.
- MOND (Modified Newtonian dynamics) would become a phenomenological outgrowth of QG at galactic scale, not an alteration of fundamental theory.

2 Quantum Foundations: A Realist Framework Solution

This point marks the beginning of the first part of the Trilogy, which focuses on quantum foundations (QF) and the construction of realist quantum theory in Regime 1.

2.1 Concepts and Backdrop of Quantum Foundations

This section is a direct continuation and elaboration of Sec. 1.1.

2.1.1 Preview of Nature in the Quantum Realm

Two key positions on what quantum physics and reality is like, according to the realist framework, are spelled out. They lay the groundwork of some core concepts and terminology.

2.1.1.1 Dichotomy of Structure: W- and P-state

In the realist framework, quantum reality is a dual ontology consisting of two components: W-state and P-state. W-state is wave-like and an ontic generalization of the wavefunction in conventional QT. It is regarded as the concrete *physicality* of the microdomain and the fundamental constitution of all matter-energy in the universe (with the technical exception of gravitational self-energy). W-state is all that we ever touch or see in experiment, and describing and modeling it correctly is the chief objective of QT.

For the most part, W-state is smooth and continuous and evolves deterministically, much like in the Schrödinger equation, and the *illusion of locality* is upheld. Bell's analysis, however, showed that entanglement phenomenology, which is predicted by conventional QT and well-verified by experiment, is fundamentally incompatible with the premise of purely local causation. It follows that W-state cannot be the whole story; it must be supplemented by P-state, which is the wavefunction incompleteness that the EPR analysis historically pointed out.

P-state is an altogether different entity from W-state. Whereas W-state is physical and local, P-state is informational and non-local. It is globally constant across entire three-dimensional *rest manifolds* that emerge from the foliated global structure of W-state, and is thus radically dissimilar to any form of classical physical state. P-state mediates and enforces entanglement effects and gives quantum systems their particle-like holistic properties. It accounts not only for EPR-like correlations but also explains, no less importantly or spectacularly, why electrons and photons show up particle-like on the detection screen in the two-slit (or one-slit) experiment. Lack of P-state cohesion was why Schrödinger's wavepackets kept falling apart.

2.1.1.2 Dichotomy of Dynamics: Rule 1 and Rule 2

In the realist framework, quantum physics is governed by two radically dissimilar dynamics principles, namely Rule 1 (unitary 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 quantum systems 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 abruptly and non-deterministically.

Historically, Rule 1 has held dominant sway and stature in traditional QT. It is the fount of the wave-theoretic mathematical machinery that enables practitioners to use QM as a predictive tool. It is superficially a classical kind of dynamic law that sat comfortably with mathematical physicists and was in keeping with the strong historical prejudice that favored the premise of determinism in all fundamental physical law.

Traditional QT, on the other hand, is diffident and ambivalent toward Rule 2. It invokes collapse processes as exceptional in nature, *i.e.*, as *ad hoc* discrete punctuations of unitary dynamics. Rule 2 is regarded merely as an instrumentalist expedient, rather than a telltale source of insight into real non-conservative physical processes. Its only purpose has been to provide the Born Rule linkage between a unitarily evolving wavefunction and actual outcomes observed in experiment.

The realist framework holds that quantum physics is a mixture and continuous interplay of Rule 1, which tends to widen the spatial expanse of the W-state, and Rule 2, which tends to narrow it and prevent it from straying far from classicality. Rule 2 is no longer regarded as merely an expedient mathematical operation or an epistemic illusion; it is real physics. Conventional QT, over the last century, has suffered from and been misshapen by lack of proper balance between the two Rules. The Schrödinger cat is ultimately a parody of the excessive authority and scope conferred to Rule 1.

2.1.2 Foundational Conundra

Why has QT been mired in foundational disarray since its very inception 125 years ago? Why has it been so conceptually intractable, to the extent that QF is arguably the single most important unsolved problem at the heart of science? This subsection explores three major facets of QF.

2.1.2.1 Quantum Story Telling

The chief symptom of foundational disarray is narrative failure. In simple terms, QM, owing to its original design as an instrumentalist tool, does not have what it takes to tell a story: a story about how Nature *is*. It is unable to answer basic questions of what, where, when, and how.

What?

After a century, there is no consensus among experts on the ontological status or meaning of the underlying subject matter of QT. 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]

Where? When?

QM 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 causal explanation. Nor can it describe wavefunction collapse in terms of a spatio-temporal distribution of local measurement-like interactions with the environment.

Conventional QT speaks in entirely different language (*e.g.*, abstract Hilbert spaces) from classical physics. Connection between the formalism and physical reality is straightforward and readily clear for the latter, but not the former. QM never discusses what Hilbert space vectors mean in concrete physical terms; it is inherently ill-equipped to address such questions and has no good answers. The entire problem of QG (until now) has had to do with the fact that QT and GR do not mesh, because the ontic structures of the two are as opposite as can be.

How?

QM cannot explain what measurement events are or delineate them as objectively real physical processes describable in straightforward physical 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.

2.1.2.2 Fathoming of Non-Locality

As a substantive technical subject, quantum physics really is conceptually hard, seemingly to the point of being utterly inscrutable. The single most difficult core challenge is to provide mechanistic explanation for *weak non-locality*, manifest in entanglement phenomenology, with the no-signaling stricture of special relativity (SR). The challenge is so centrally important to making sense of quantum physics that the theoretical minimum, in the development that follows in Sec. 2.2, is dedicated exclusively to addressing and resolving it.

Historical Synopsis

The seeds of non-local physics were sown in the formalism of traditional QT, as it originally took shape in the late 1920's, but it did not become apparent until many decades later, beginning with Bell's analysis (1964) and the Clauser-Aspect experiments (1972, 1982) that followed.

The EPR analysis (1935) of entanglement phenomenology in simple two-quanton systems was historically the first inkling of non-local causation. It correctly diagnosed the incompleteness of the wavefunction (W-state) and pointed to a key element of reality (P-state) missing from the conventional account. It threw Bohr for a loop, who was unable to come up with a coherent rejoinder. For that, he would have had to invoke non-local reasoning, but there was no conceptual foundation for non-local coordination available at the time.

Bell was the first to scrutinize the premise of *local realism* (*i.e.*, purely local causation), as a universal over-arching principle. He showed that: (i) Conventional QT is fundamentally incompatible with local realism. (ii) Violation of local realism translates experimentally into the CHSH inequalities (*i.e.*, strong entanglement correlations exceeding what is allowed under the supposition of local realism). The CHSH inequalities were found to be violated in the Clauser-Aspect experiments, and non-locality became established empirical fact.

No-Signaling Stricture on W-state Only

The realist framework solves the challenge as follows:

- First, it establishes rest manifolds as the substrates on which P-state lives. The manifolds are 3D spatial structures that emerge globally, as foliation, from W-state, across all matter-energy in the universe. They have two key properties:
 - relativistic invariance (*i.e.*, any two observers will agree on whether any two points belong to the same manifold, \mathcal{M}).
 - global hyperbolicity (*i.e.*, any two points in \mathcal{M} are space-like separated).
- P-state is essentially a multivariate probability density function (PDF) governing outcomes realized at all local measurement sites on \mathcal{M} . Under the premise of local realism, the PDF factorizes as a product of univariate local PDF's applicable to the measurement sites. In the general case of non-locality, the PDF is unfactorizable.
- P-state is "private" to the rest manifold, *i.e.*, not observable or controllable by the W-state at any of the measurement sites or elsewhere on \mathcal{M} . The W-state and P-state thus occupy two separate ontic domains, separated through two information-theoretic criteria that ensure that the no-signaling stricture, for W-state, is enforced:
 - No contrived intervention by the W-state at any site can exert controllable influence on the evolution of the W-state elsewhere on \mathcal{M} .
 - W-state at remote sites cannot be inferred from observation of the W-state locally at any site.
- The *only* way of upholding no-signaling is to require that the measurement outcomes be *absolutely random*, in the sense set forth in traditional QT. Absolute randomness thus becomes elevated to theorem stature.
- The no-signaling stricture applies *only* to W-state, which embodies all physicality in the universe. P-state, as purely informational state, is exempt.

Ontological Status of the Wavefunction

Conventional QT has been troubled by the long-standing issue of whether the wavefunction is an epistemic or ontic entity. The traditional majoritarian view holds that it is epistemic, *i.e.*, only exists in the minds of physicists and as a written symbol. The realist framework, however, shows that to be a diffident retreat, stemming entirely from lack of a good mechanistic solution squaring non-locality with no-signaling. After all, the entire worry was about *how* the global coordination required to effect wavefunction collapse could be mustered. By providing a definitive solution in the theoretical minimum, the RQF resolves the issue for once and for all: W-state is decidedly ontic.

2.1.2.3 Measurement Problem

The term *measurement problem* is a multifaceted constellation of open questions and issues at the heart of QF. It includes, but is not limited to the following questions.

Is Rule 2 Epistemic Illusion or Real Physics?

Conventional QT has been troubled by the long-standing issue of whether Rule 2 signifies true departure from unitary Rule 1 dynamics or is epistemic illusion. The traditional dispensation treats Rule 2 as an expedient instrumentalist intervention to convert a unitarily evolving wavefunction into concrete outcomes probabilistically via the Born Rule. It is silent and non-committal, however, on the underlying physics. It does not explicitly maintain that Nature *is* absolutely random in its selection of outcomes; it instead pitches absolute randomness as an epistemic blackbox. After all, the outcomes are all that we know and ever see; what produces actual outcomes in individual systems is fundamentally impervious to deeper explanation, the orthodoxy maintains.

The traditional stance thus leaves open the door that the true underlying physics in the microdomain *may be* deterministic, despite all appearances of being otherwise. But Copenhagen officially denies deep reality in the microdomain. In practical terms, the stance means that deterministic Rule 1 formalism is conferred lenient reign and unchecked scope. Two simple examples are telling:

- Two of the three historically influential alternatives to standard QT, namely the pilot wave theory of De Broglie and Bohm (dBB) and Many Worlds (MW), are ostensibly deterministic.
- Time-dependent perturbation theory (TDPT) strives to be Rule 1 only, but it improperly overextends the Hamiltonian formalism to model what are clearly irreversible, dissipative, non-conservative processes (*e.g.*, spontaneous emission, tunneling processes).

What Triggers Measurement Processes?

QM is reticent and offers little insight into the causative mechanics that trigger measurement events. At most, it indicates that it has something to do with contrived intervention in the laboratory, using a macroscopic instrument. That, however, leaves the impression, badly distorted by instrumentalist bias, that Rule 2 has *only* to do with contrived experimental interventions and therefore has no independent role in Nature, far removed from physics laboratories and physicists.

Where and When does Measurement Occur?

QM is unable to pinpoint measurement events in straightforward manner as objectively real physical processes. Consider the simple scenario of a silver atom running through a Stern-Gerlach magnet. We ask where and when does the measurement, which determines whether the atom will emerge with spin up or down, occur. The orthodox dispensation informs us that that is a meaningless question. It is not the job of QM, the official stance goes, to answer any question about an individual atom; it is only about probabilities and prediction.

Are measurement processes for real? That is a question on which it is easier to prove a negative than to prove a positive. A measurement event can be said conclusively *not to have occurred* if an interference pattern is observed, such as in the two-slit experiment or in a Mach-Zehnder interferometer.

The realist framework will revisit the SG experiment further on. It will transform the experiment from a mysterious, probabilistic oracle into a comprehensible, causal, and dynamic physical process.

How are Actual Outcomes Determined?

This is the most difficult question. In the realist framework, the answer emerges from the mechanistic solution of the theoretical minimum. The solution demonstrates *how* a random sample can be drawn from an unfactorizable PDF, such that the statistical predictions of standard QT are faithfully reproduced.

Does the RQF Solve the Measurement Problem?

Not exactly. The RQF is a great step beyond standard QT in that it clarifies what quantum measurement means, as a physical process, but it does not resolve all of the ambiguity.

As a simple example, consider spontaneous emission in an atom. There are two alternative conjectures as to what happens:

- **Early Decision Scenario:** The photonic W -state emerging from the radiative drop is essentially a pencil beam. That is, the momentum of the photon (and the equal and opposite recoil of the atom) is determined amidst the emission process. It is thus decided beforehand that only detectors intercepting the pre-determined emission direction stand any chance of detecting the photon.
- **Late Decision Scenario:** The photonic W -state is a spherically symmetric shell. All detectors anywhere on a sphere centered around the atom have *a priori* equal chance of detecting the photon. The direction of the photon momentum and recoil of the atom is not decided until retroactively after a detector registers a positive detection (Sec. 2.3.4.4).

It may be that the early and late decision scenarios are undecidable by experiment, in which case there remains unresolved latitude in theoretical models (in violation of Leibniz' principle of *sufficient reason*). Although one model is objectively closer to the truth than the other, the adoption into *de facto* practicing theory then becomes a matter of aesthetic preference and congruity with other physical principles. For example, the late decision scenario, with the spherically symmetric shell, is more in keeping with established atomic physics than the early decision pencil beam.

Consciousness

The notion of human consciousness as having fundamentally to do with wavefunction collapse is a parody of the lack of good answers to the preceding questions. Taken seriously, it implies that quantum physics, despite its supposedly all-encompassing scope, could not exist as such until intelligent life evolved into existence on Earth.

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.

Can a cat or mouse change the universe by looking at it? The realist framework regards the retina as a hard backstop, which is as effective as any measuring instrument to precipitate collapse. In this respect, the observer initiates and indeed participates actively in the creation of new reality. Note, however, that there need be nothing 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.

2.1.3 Historical Prejudices

As was noted in the introductory remarks in Sec. 1.1.2, QF is not merely an assortment of technical riddles. It is integrally interwoven with deep-seated powerful prejudices, which historically had great power over the minds of the 1927 Solvay conferences attendees and their many intellectual descendents. They had fateful bearing on the gestation of traditional QT and the course that science would subsequently follow.

2.1.3.1 Determinism

One of the most important and powerful prejudices was the predilection for determinism in dynamic law and physical theory.

Historical Tyranny of Determinism

It began with the spectacular successes of astronomers in predicting eclipses. It was a watershed in the birth of science and a triumph of human reasoning capability over the whims of the gods, but it also made the primacy of

determinism a powerful and enduring cultural narrative. Galileo's experiments, which showed that deterministic law also applies in terrestrial settings, buttressed that, and Newton made the crucial connection between the heavens and Earth.

The enticing narrative of determinism went to scientists' heads and begat hubris and overconfidence. Laplace's demon was a fallacy of grand extrapolation. It overgeneralized from, and conferred excessive authority and scope to, deterministic celestial and terrestrial dynamic law, whose exceptional and particular circumstances were overlooked. They apply only in rarefied low-entropy settings. The grand inferential leap that declared determinism to be all-encompassing metaphysical principle was grotesque overreach. The excessive favoritism toward Rule 1 and denigration and marginalization of Rule 2, amidst that historical backdrop, was no accident.

Boltzmann's Impasse

The realist framework offers a short punch answer to the measurement problem: Take Rule 2 seriously. That was arguably the solution that was hiding in plain sight all along; they should have known better. Everyday life, as we plainly experience it, quite obviously does not exhibit time-reversal symmetry. The oversight is exemplified most poignantly by Boltzmann, who at one time seemed to have succeeded in proving that macroscopic irreversibility is a statistical consequence of time-reversible microscopic dynamics, but he became fazed when it was found that there are just as many high-entropy microstates that can evolve to low-entropy states as vice versa. Had it occurred to him that the microscopic dynamics might be fundamentally irreversible, the arrow of time could have been solved in the 19th century.

The quantum founders perpetuated the mistake. They misjudged quantum physics as being fundamentally more deterministic than it actually is. Smooth unitary evolution was seen as the true physics, whereas messy probabilistic wavefunction collapse was an embarrassment that had to be accommodated grudgingly and minimized.

Realist Perspective on Rule 1 and Rule 2

The realist framework holds that quantum physics, both in Nature and in experimental settings, is best visualized as *islands of order* (coherence) in seas of chaos. Entropy is fundamentally a measure of the degree of Rule 2 (decoherence) dominance over Rule 1.

Quantum textbooks, being heavily biased toward Rule 1, give the impression that eigenfunction solutions (*e.g.*, standing wave modes in Planck's blackbody cavity) represent literal truth. The realist framework dispels that notion; it instead maintains that the eigenfunctions are meta-stable solutions. They signify the islands of greatest extent, both spatially (*e.g.*, filling the cavity volume) and temporally, that can be achieved amidst the backdrop of chaos.

2.1.3.2 Instrumentalism

Instrumentalism, as a methodological stance toward scientific practice and epistemology, is also noteworthy historically as a powerful prejudice, but for reasons more subtle than the hubris of determinism.

Whitebox and Blackbox Physics

The simplest and most direct understanding holds that: (*i*) realism is whitebox physics, whereas (*ii*) instrumentalism is blackbox physics.

Realism is a highly ambitious program. It seeks not only powerful theoretical models and calculational tools whose formal content maps directly to underlying deep reality; it also aims to resolve the foundational conundra, the most important of which is ultimately narrative clarity. However, it depends heavily on the premise of an information- and knowledge-rich working environment to provide the necessary whitebox insight into the detailed nature of the underlying physics.

Blackbox physics is the less glamorous state of affairs when investigators operate in impoverished knowledge environments, as they were in the days of thermodynamic and early atomic work. Instrumentalism, as it came to shape the formulation and trajectory of QM, was ultimately the pessimistic conviction that *physics would always be like that*.

Mathematical Model of Instrumentalism

A simple control-theoretic model provides general mathematical insight into the operational nature of blackbox physics and its limitations. Investigators do not have direct visibility into the internal physical state of the underlying system (*i.e.*, the noumena of Kant's world). They only have access to actuators and sensors strapped onto the plant. Working only with the actuator and sensor signals (Kant's phenomena), can they learn anything about the interior?

Partial knowledge is indeed attainable. If the system is excited with white noise through the actuators and the cross-correlation power spectra with the sensor outputs are observed, extensive system identification analysis (*e.g.*, singular value decomposition of the resulting Hankel matrices) enables a Kalman filter predictive mapping between inputs and outputs to be constructed. Moreover, the singular value rolloff enables the state dimensionality of the plant to be estimated.

In information-theoretic terms, the Kalman filter, which Kant would regard as *theory*, is analogous to the instrumentalist interpretation of the Schrödinger equation, and the internal state of the filter is analogous to the instrumentalist wavefunction. The internal state of the filter, which is a synthetic computational state, is indirectly related to the physical state of the plant (through an unknown similarity transform). That is, the filter state reveals only the eigenstructure of the plant dynamics. Other matrices in the Kalman filter predictor are similarly related indirectly to couplings between the instrumental signals and the plant states. Because of the indirect and tenuous correspondences to the plant states, instrumentalists can insist that the filter states are pragmatically useful but also "meaningless".

2.1.3.3 Epistemic Diffidence

Positivism

Logical positivism is closely related to, and historically evolved in tandem with, instrumentalism. Positivism was more radical and went further to circumscribe the bounds of human thought capacity, imagination, and vocabulary. The Copenhagen dispensation, which became the dominant articulation of hard-line anti-realist positivist dogma, has tirelessly browbeaten practitioners and students with the core tenet that it is fundamentally beyond the bounds and capabilities of the human intellect and imagination to envisage what the quantum world is really like. More basically, it tells us that it is fundamentally impossible to think, speak, or reason non-classically. The development of the relational W-state ontology, in what follows, pointedly rejects that discouragement.

The Legacy of Copenhagen

Copenhagen was not merely a codification of instrumentalist conservatism and rigor. Under Bohr and Rosenfeld, it hardened into an explicitly obscurantist ideology of epistemic defeatism. The veneer of positivism was wielded as a political tool and disciplinary gate-keeping mechanism to silence and discredit foundational unease.

And even that is understatement. Copenhagen was not a scientific stance; it was ultimately a cult of intellectual repression. It actively discouraged and socially marginalized inquiry that sought to explain QM more deeply or probe foundational issues. It demanded unquestioning fealty to mathematical formalism and the unnatural suppression of curiosity and questioning.

2.1.4 Classical Reality

The quantum realm is profoundly different from classical physics in numerous fundamental respects. Those differences have much to do with what has long made quantum phenomenology and theory conceptually intractable and baffling for so long. It is thus necessary to take explicit note of essential characteristics of classical theory, often taken for granted as "common sense", that will cease to hold as we delve into the quantum realm.

2.1.4.1 Classical Physical Theory

Local Reality

In classical physics, all reality is local. Local reality can be represented mathematically by tensor fields, *i.e.*, scalars, vectors, or higher-order tensors. In electromagnetic theory, for example, it is the combination of an electromagnetic field tensor (or vector potential) and a current density 4-vector. In GR, 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 ontic structures. The physical reality of a classical system is the set of tensor values at the points it occupies.

Global Reality

Any notion of global reality, in relativistic classical theory, is completely precluded by the axiomatic premise that no simultaneity hyperplane has preferred stature. Any notion of strong non-locality across simultaneity hyperplanes could result in causal vitiating (*e.g.*, preventing one's parents from having met) and is therefore disallowed. Strong non-locality, in principle, could be countenanced in Newton's absolute time in the non-relativistic limit ($c \rightarrow \infty$); causal vitiating would not arise because of the feedforward temporal structure (unlike in SR).

Determinism and Time-Reversal Symmetry

Common understanding holds that classical physics is inherently deterministic, but that is actually not true. There is no fundamental principle that precludes the injection of *innovation* (*i.e.*, the purely stochastic output of a random number generator) into classical dynamic law. Nor is there anything fundamentally sacrosanct about time-reversal symmetry. It is perfectly tenable to inject innovation, which has causal influence in the fore but not the aft light cone of the injection event.

Local Causality

The structure of classical physical theory is *locally causal* in that it admits only dynamics law such the state at any point, \underline{x} , depends only on the states at points on the region of any Cauchy surface transected by the aft light cone of \underline{x} , assuming no innovation injection in the interior of the enclosed cone volume.

Reductionism

From the wholly local character of classical reality, it follows that all ontic structure and dynamic law in classical physics is reductionist through-and-through in its architecture. Simply put, the whole is always the sum of the parts - never more or less. The reductionist architecture can be given formal expression in the framework of relational mechanics, such as developed by Barbour [1]. Relational mechanics, as a formal logic and reasoning system, permits only propositions formulated in terms of: (*i*) local states (tensor values), and (*ii*) spatio-temporal relations between points of whose states we speak.

2.1.4.2 Classical Wave Ontology

Classical Waves as Emergent Phenomena

From the strictly local structure of physical state ontology, it follows that all classical waves are emergent phenomena. They are all "crowd waves", in a specific technical sense based on the collective of locally oscillating tensor field values.

Fourier Analysis

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-frequency¹ domain, and vice versa. Mathematically, either representation is complete and convertible to the other.

Classical waves are said to be *ontically primary* on the time domain, as function definition on space-time is the directly palpable and visualizable physical reality. The frequency domain is more abstract and thus considered secondary.

Several key insights follows from the strictly local structure of the ontology:

- Fourier analysis, in its familiar conventional form, is inextricably the staple mathematical framework and analytic tool of classical wave-theoretic analysis. The mathematical complementarity of conjugate domain pairs (*e.g.*, time and frequency, wavenumber and optical path length) is an inherent feature of classical wave theory.
- If we examine a wave phenomenon locally, all that we see is a single tensor value. The waviness becomes apparent only when the phenomenon is sampled over a finite region of space-time (spanning at least several wavelengths or cycles). Alternatively stated, classical waves are not *locally resolvable*.
- The use of complex numbers in classical physics and electrical engineering, to represent oscillatory quantities, is solely a matter of mathematical convenience to simplify analysis. In classical wave-theoretic application problems, the real part of the complex-valued quantity represents the physical ontology of interest. In the construction of the complex-valued quantity, the imaginary part is merely the Hilbert transform of the real part and thus imparts no additional physical content.

2.1.5 Quantum Reality

A few (of many) non-classical facets of quantum reality are spelled out in this subsection.

2.1.5.1 Wave-Particle Duality

Wave-particle duality is one of the most profound and puzzling facets of quantum ontology. It is not merely the saw that a quantum object is either a wave or a particle, depending on how an experimenter chooses to measure it. It is fundamentally the question of how an object, composed of wave-stuff (W-state), can exhibit particle-like holism. The question never arises in classical physics, wherein all substance (matter-energy) is either particle-stuff or field-stuff. Wave phenomenology is only emergent from field-stuff; there is technically no such thing as wave-stuff *per se* in the classical realm.

In the quantum realm, by contrast, wave-stuff is real as such, and a new conceptual arsenal and vocabulary is needed for it. The hard technical question at the heart of wave-particle duality is *how* wave-stuff can be holistic in fashion that respects SR. The answer is that it relies on non-local internal mediation via P-state.

2.1.5.2 Quantons

The generic term *quanton* signifies the smallest indivisible unit of particle-like holism (lumpiness) in its W-state. There exists a small inventory of quanton types, which is represented by the Standard Model. Alternatively interpreted, quantons are the smallest assemblages of W-state that can be considered quantum systems.

Quantons are *not* particle-stuff (*i.e.*, hard classical billiard balls). They are wave-stuff and, as such, have ontic stature *as waves*. But whereas classical wavepackets disperse and fall apart, quantons are aggregations of W-state endowed with a distinctly quantum cohesion owing to internal P-state mediation. Particle likeness is an emergent result of P-state coordination, not a fundamental property of W-state *per se*.

¹For brevity, these will be referred to henceforth simply as the time and frequency domains.

2.1.5.3 Non-Reductionism

A distinctly quantum property of W-state is that it is *not* reductionist. It is not the case that the whole is the sum of the parts. Specification of the local state at all points occupied by a quanton does not yield a complete representation of its W-state. This is fundamentally unlike any form of classical state or phenomenology. The non-reductionist character of W-state can only be described and modeled in terms of *relational ontology*, which is introduced and developed in detail in the theoretical minimum, which follows next. W-state is technically local reality, but the relational ontology requires us to understand it in entirely new non-classical terms.

2.1.5.4 Local Resolvability of Wave-Stuff

Fourier analysis is specifically designed for the analysis of functions ontically primary on a single domain. It relies on the physical premise of field-stuff ontology, which inherently lacks the cohesiveness of W-state. It is therefore ill-suited for quantum physics. The conventional wavefunction, which is ontically primary on the space-time domain, must be replaced by something more powerful and specifically designed for the description and modeling of wave-stuff. The distinctive mathematical property of wave-stuff is *local resolvability* of the wave components, which is naturally described in terms of functions ontically primary on the joint time-frequency domain.

2.2 Theoretical Minimum of W-state

The *theoretical minimum* of the RQF is specifically the foundational conundrum of squaring weak non-locality with SR, as mentioned in Sec. 2.1.2.2.

2.2.1 Quantum Waves

2.2.1.1 Quantum Wave Elements

Consider the simplest mathematical abstraction of quanton W-state, which is a pure *quantum wave element* (QWE). It can be represented by a wavefunction, *viz.*,

$$\psi(\underline{x}) = e^{i(\underline{k} \cdot \underline{x})} \quad (1)$$

which employs 4-vector notation $\underline{k} \equiv (\underline{k}, \omega/c)$ and $\underline{x} \equiv (\underline{x}, ct)$, with inner product definition $\underline{k} \cdot \underline{x} \equiv \omega t - \underline{k} \cdot \underline{x}$. \underline{k} and \underline{x} are respectively ordinary wavenumber and position vectors in 3D space.

QWE's are a space-filling² abstraction used for the sake of mathematical purity. The simplest abstraction of W-state, they are the logical starting point for its theoretical development.

2.2.1.2 Physical Interpretation of QWE's

The W-state, at any point, \underline{x} , occupied by a quanton, is locally resolvable into a multitude of wave components, characterized by different wave vectors (\underline{k}). Each wave component, which is physically real at local scale, is described mathematically by the QWE tangent to it.

As was mentioned in Sec. 2.1.3.1, the real state of quantum affairs, both in Nature and in the laboratory, consists of islands of order (coherence), which are characterized by various spatial and temporal scales. The order can be described and modeled mathematically in the language of differential geometry, wherein QWE's are locally tangent to curvilinear paths defined by physical coherence relations.

2.2.2 Relational Ontology of QWE's

2.2.2.1 Referenced Mappings

The concept of a *referenced mapping* from the local quantum state at each space-time point to the set of complex numbers, \mathbb{C} , is first introduced. The relational ontology posits the following constructive definition:

²“Space-filling” really meaning space-time-filling.

- For any given reference point, $\underline{x}_{\text{REF}}$, the local quantum state may be assigned an arbitrarily chosen non-zero complex number, z_{REF} .
- Given $\underline{x}_{\text{REF}}$ and z_{REF} , a referenced mapping satisfying the reference condition is uniquely determinate.

The first criterion relies on the premise that the local quantum state at the reference point is non-zero, which is always the case everywhere for pure QWE's. The referenced mapping obtained in the second criterion is said to be *narrowly representative* of the QWE. Mathematically, a referenced mapping, ψ , is a function whose domain is space-time and whose range is \mathbb{C} .

2.2.2.2 Equivalence Class of Referenced Mappings

The relational ontology holds that for any given referenced mapping, ψ , from space-time to \mathbb{C} , $a\psi$, where a is any non-zero complex number, is an equally valid referenced mapping and also narrowly representative of the QWE. $a\psi$ is defined mathematically simply as:

$$a\psi \equiv \lambda \underline{x} : a\psi(\underline{x}) \quad (2)$$

The set of valid referenced mappings constructible from Eq. 2 is an equivalence class, \mathcal{E} . Given any two referenced mappings, constructed using different and unrelated choices for $\underline{x}_{\text{REF}}$ and z_{REF} , the two are equivalent modulo some non-zero multiplicative constant, a , in accordance with Eq. 2.

The relational ontology holds that \mathcal{E} is the single definitive mathematical representation of the QWE. \mathcal{E} is said to be *widely representative* of the QWE, whereas the elements of \mathcal{E} (*i.e.*, the referenced mappings) are said to be narrowly representative.

2.2.2.3 Relational Propositions

A proposition is considered valid in the relational ontology - or, equivalently stated, to have stature as a *relational proposition* - if, by definition, the following criteria hold:

- The proposition is meaningful and decidable for each element (referenced mapping) in \mathcal{E} ;
- The proposition is either unanimously true or unanimously false among all elements of \mathcal{E} .

Formally, a relational proposition, P , is valid on the W-state of the QWE (denoted as Ψ) and evaluates to true if the following holds:

$$P(\Psi) \equiv \text{ALL}_{a \in \mathbb{C} - \{0\}}(P(a)) \quad (3)$$

in which $P(a)$ denotes the evaluation of the proposition on the particular referenced mapping in Eq. 2. From the definition in Eq. 3, the following lemmae readily follow:

- If P is a relational proposition, so is NOT(P), *viz.*,

$$\text{NOT}(P) = \text{NOT}(\text{ALL}_a(P_1(a)), \dots, \text{ALL}_a(P_n(a))) \equiv \text{ANY}_a(\overline{P(a)}) \quad (4)$$

which of course evaluates to the negation of P .

- If $\{P_1, \dots, P_n\}$ is a finite set of relational propositions, the conjunction (AND) is also relationally valid, *viz.*,

$$\text{AND}(P_1, \dots, P_n) = \text{AND}(\text{ALL}_a(P_1(a)), \dots, \text{ALL}_a(P_n(a))) \equiv \text{ALL}_a(\text{AND}(P_1(a), \dots, P_n(a))) \quad (5)$$

The arguments of the rightmost expression in Eqs. 4-5 are straightforward to evaluate within conventional Boolean logic.

- DeMorgan's Law holds and yields relational definition of OR(P_1, \dots, P_n) in the expected way.

2.2.2.4 Implications of the Relational Ontology

The relational ontology circumscribes the structure and content of meaningful statements that can be made about a QWE, as a physical entity:

- Uni-predicate propositions, which speak only the local quantum state at a single point, are not powerful. All that can be said about a local quantum state, in isolation from the rest of the QWE, is that it has some non-zero amplitude and some indeterminate phase.
- Bi-predicate propositions, by contrast, yield quantitative information about the *phase difference* between the local quantum states at two different points.

It requires us to think of common mathematical entities in distinctly non-classical ways. For example, complex numbers are such that real and imaginary part are deemed meaningless and inaccessible. Formally, operators to extract real or imaginary part from a complex number are undefined. Similarly, phase differences are such that minuend and subtrahend are meaningless and inaccessible.

Quantum Wave Ontology

The relational ontology explains fundamental differences between classical and quantum waves. In a classical wave, local state is represented by a mathematically real-valued tensor quantity that 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.

Complex Numbers in Quantum Theory

It is evident that complex numbers are inextricably interwoven with the mathematics of QT, fundamentally unlike in any classical theory. In classical theory, the real part of complex-valued quantities represents physical ontology of interest, whereas in QT, real and imaginary parts of W-state expressions (*i.e.*, widely representative equivalence classes) have no physical significance of their own and are formally undefined.

2.2.3 Quantitative Analysis of W-state in QWE's

2.2.3.1 De Broglie Relation

QWE's, of the simple kind included in the theoretical minimum, are governed by the De Broglie relation, *viz.*,

$$\underline{p} = \hbar \underline{k} \quad (6)$$

Eq. 6 indicates that \underline{k} is directly proportional to the energy-momentum, $\underline{p} \equiv (\underline{p}, E/c)$, through Planck's constant, *viz.*,

$$E = \hbar\omega \quad (7a)$$

$$\underline{p} = \hbar\underline{k} \quad (7b)$$

in which E denotes the combination of rest and kinetic energy, *viz.*,

$$E = c(m^2c^2 + p^2)^{1/2} \quad (8)$$

in which m is the quanton rest mass.

2.2.3.2 Quantum Wave Elements at Rest

Whereas \underline{k} is a property of the QWE itself, as W-state, \underline{p} is a property of the quanton itself, as a whole quantum system. It is noteworthy at this stage only in that it reveals the oscillatory frequency of the W-state in the rest frame of the quanton, which is equal to the Compton frequency *viz.*,

$$\omega_0 \equiv mc^2/\hbar \quad (9)$$

In the QWE rest frame, $\underline{k} = \underline{0}$, and Eq. 1 simplifies to

$$\psi(\underline{x}) = e^{i\omega_0 t} \quad (10)$$

Eq. 10 states that in the rest frame, the W-state is homogeneous spatially and exhibits only temporal variation. In the general case of an observer³ moving relative to the rest frame, \underline{k} is non-zero, and the W-state varies spatially and temporally.

2.2.3.3 Operational Definition of W-state Interference

The QWE, in its rest frame, is said to pulsate at the Compton frequency, ω_0 . What does that mean physically? What is the physical rationale for the referenced mappings postulated in the formal development of the relational ontology?

Physical rationale is provided through an operational definition, which envisages a virtual procedure through which the W-state can be manipulated (mathematically, not physically), *viz.*,

- **Copy:** A virtual copy of the W-state is made. This is simply the application of an identity operator mathematically. It does *not* signify a physical cloning of W-state, which is well-known to be disallowed.
- **Transform:** The copy is transformed, based on conventional types of transformation operators familiar from standard QT.
- **Superpose:** The transformed copy is overlain (superposed) with the original, and the resulting interference is noted.

In the case of the QWE in its rest frame, the transform operation consists simply of shifting the W-state temporally by a half-period, *viz.*, $T/2 = \pi/\omega_0$. Superposition of the time-shifted copy and the original then results in destructive cancellation.

2.2.3.4 Sequential and Lateral Coherence

The QWE in its rest frame clearly illustrates and distinguishes two forms of coherence that characterize quantum waves. One is *sequential coherence*: At any given fixed position, \underline{x} , the phase increases in predictable fashion (for an isolated quanton, linearly) over time. Such one-dimensional filaments of W-state within a quantum wave are regarded as having physical unity in their own right and go by the term *long thread*. Long threads of isolated quantons are straight lines.

The second form is *lateral coherence*, which is the fact that long threads occur in bundles. They are flanked by parallel long threads in phasal sympathy. This too is a physical unity, which goes by the complementary term *wide thread*.

2.2.3.5 Local Interference

Consider the simple scenario of two QWE's that are equal in frequency (in some reference frame) but differ in direction and amplitude, *viz.*,

$$\psi(\underline{x}) = c_1 e^{i(\omega t - \underline{k}_1 \cdot \underline{x})} + c_2 e^{i(\omega t - \underline{k}_2 \cdot \underline{x})} \quad (11)$$

³Observer in the passive sense of SR, not the active sense of traditional QT.

in which $|\underline{k}_1| = |\underline{k}_2|$ and c_1 and c_2 are non-zero amplitudinal coefficients (complex numbers) in some referenced mapping. The equivalence class, \mathcal{E} , widely representing the W-state is spanned by multiplying c_1 and c_2 both by a common non-zero multiplier (a , as in Eq. 2).

What does the relational ontology permit us to say about the W-state at a fixed spatial location, \underline{x} , but viewed over an extended temporal interval? Without loss of generality, it can be said that the W-state at \underline{x} pulsates at frequency ω with amplitudinal magnitude (complex modulus) equal to

$$|\psi(\underline{x})| = |c_1 e^{-i\mathbf{k}_1 \cdot \underline{x}} + c_2 e^{-i\mathbf{k}_2 \cdot \underline{x}}| \quad (12)$$

Eq. 12 indicates that the amplitudinal magnitude, which determines the local interference, varies spatially, provided that \underline{k}_1 and \underline{k}_2 differ directionally. The right-hand side indicates that the interference is spatially periodic. The interference is most constructive (most destructive) at \underline{x} such that the right-hand side of Eq. 12 is maximal (minimal) with respect to \underline{x} .

The QWE's in Eq. 12 both belong to the same quanton. At non-relativistic velocities, ω differs negligibly from ω_0 in both terms. It follows that the spatial pattern of interference is robustly frequency-independent.

2.2.4 Ontic Primacy on the Joint Time-Frequency Domain

2.2.4.1 Local Resolvability

Local inspection of the W-state - not only over a small neighborhood, but also at literally just a single point - reveals that the W-state expression in Eq. 12 consists of two QWE components, characterized by wavevectors \underline{k}_1 and \underline{k}_2 and amplitude ratio c_2/c_1 .

That the wave vectors, amplitude ratios, and local interferences can be recovered from local inspection of the W-state indicates that wave properties are physically real in their own right and exist locally - well below wavelength scale. This is the essential nature of wave-stuff.

2.2.4.2 Superposition

The formal W-state expression for the superposition of two QWE's is:

$$\Psi(\underline{x}) = \Psi_1(\underline{x}) \oplus \Psi_2(\underline{x}) \quad (13)$$

Eq. 11 is narrowly representative of the same W-state combination widely represented by Eq. 13, but the notation in the former is much more familiar. Whereas the plus sign in Eqs. 11-12 denotes ordinary addition among complex numbers, the ' \oplus ' symbol in Eq. 13 denotes a *local superposition* operator. It is an addition-like operation, but differs from ordinary addition in that it permits the terms to retain their identifies and content while collocating in space-time.

2.2.4.3 Flexible Wave Mechanics

Eq. 13 generalizes as the Fourier decomposition of W-state, *viz.*,

$$\Psi(\underline{x}) = \int \tilde{\Psi}(\underline{k}) e^{i(\underline{k} \cdot \underline{x})} d\underline{k} \quad (14)$$

in which the integration denotes superposition, and the \underline{x} -dependence of the QWE terms is concentrated in the phase factors.

Eq. 14 is the expression of rigid wave mechanics in the formalism of W-state. It is a superposition of pure space-time-filling QWE's, each consisting of infinitely wide bundles of infinitely long straight rigid threads. The compactness (*i.e.*, square integrability) of the wavefunction-like quantity on the left-hand side relies on destructive interference, brought about by phase cancellations, among the threads at points far from the wavefunction center.

Ontic primacy on the joint time-frequency domain implies that the amplitudinal coefficient, $\tilde{\Psi}$, is actually a function of both \underline{x} and \underline{k} . It follows that long threads are no longer rigid, but flexible. W-state ontology and dynamics thus become truly local. Local, that is, insofar as the *illusion of locality* is upheld in the W-state dynamics; the important point, for now, is that the rigidity of traditional wave mechanics is shattered.

2.2.4.4 Derivation of the Conventional Wavefunction from W-state

In the general case of W-state with flexible long threads, Eq. 14 takes the modified form:

$$\Psi(\underline{x}) = \int \tilde{\Psi}(\underline{k}, \underline{x}) e^{i(\underline{k} \cdot \underline{x})} d\underline{k} \quad (15)$$

which makes it explicitly clear that $\tilde{\Psi}$ is ontically primary on the joint time-frequency domain. Eq. 15, which is exact, demonstrates how a quantity akin to the conventional wavefunction (on the left-hand side) can be derived from the general expression for W-state (on the right-hand side). Proceeding in the opposite direction from wavefunction to W-state, however, is now precluded because of the \underline{x} -dependence in $\tilde{\Psi}$.

Eq. 14, which is a conventional Fourier transform, can still be used to obtain $\tilde{\Psi}(\underline{k})$ formally from $\Psi(\underline{x})$, but the resulting quantity is merely a superposition of rigid waves, which the RQF deems artificial and not physically realistic. The wavefunction therefore does not reproduce the locally flexible structure of $\tilde{\Psi}(\underline{k}, \underline{x})$.

Rigid wave mechanics is fundamentally incompatible with any premise of local wave-stuff dynamics. Local inspection of the W-state, according to Eq. 14, yields $\tilde{\Psi}(\underline{k})$, which applies throughout the entire wavepacket volume. It would follow that the entire W-state of the quanton can be inferred from analytic continuation of the local W-state.

2.2.4.5 Multi-Situationality

The integration expressions on the right-hand sides of Eqs. 13-15 denote superpositions, the various terms in which all “belong” to the one quanton but speak of different velocity directions and magnitudes. As such, the terms in the superposition represent dissimilar *classical situations*. A classical particle can be in only one place and have only one velocity at any instant. Furthermore, the fact that W-state is spatially spread out implies that quantons exist in multiple places at once.

The third distinctively non-classical key feature of W-state ontology⁴ is therefore *multi-situationality*, which simply means the coexistence of mutually incompatible classical situations within a quantum system. In W-state parlance, the different situations are said to collocate and interpenetrate one another. Quantum waves retain their separate identities, whereas classical waves become blurred when they collocate.

2.2.4.6 Ontic Uncertainty

Return to the language of classical particle trajectories, in the context of threads, does *not* signify an abandonment of the Heisenberg uncertainty principle (HUP), which is simply a theorem of Fourier analysis. It points out that there exists an irreducible tradeoff between resolutions in any Fourier conjugate pair of domains. It is based on the mathematical premise of ontic primacy on a single domain, and thus implicitly the physical premise of rigid wave mechanics.

Despite those narrow assumptions, HUP empirically is extremely robust and virtually inviolate. In realist QT, it is superseded by an *ontic uncertainty principle*, which is ultimately a statement about: (i) mandatory existence of multi-situationality, and (ii) stiff bounds on W-state compressibility. Application of the new uncertainty principle to a free quanton is demonstrated in Sec. 2.4.1.3.

2.2.5 Emergence of Global Structure from W-state

2.2.5.1 Multi-Quanton W-state

What has been described and developed thus far is single-quanton W-state. We next consider the more general scenario of N quantons coexisting in space-time, the composite W-state of which is denoted as:

$$\Psi(\underline{x}) = \Psi_1(\underline{x}) \uplus \Psi_2(\underline{x}) \uplus \dots \uplus \Psi_N(\underline{x}) \quad (16)$$

⁴The first two being (i) the relational ontology and (ii) ontic primacy on the joint domain.

in which \uplus denotes a set-theoretic union operator. The right-hand side of Eq. 16 denotes a bagful of single-quanton W-states, all cohabiting the same volume of 4D space-time.

In the simplest case, which suffices for the theoretical minimum, the quantons are distinguishable by virtue of being of different types. It then follows that the right-hand side of Eq. 16 is a rigorous expression of an unordered union.

Dissolution of Configuration Space

Conventional QT is steeped in the formal concept of abstract $3N$ -dimensional configuration space. The RQF instead regards Eq. 16 as an expression of N quantons being collocated and interpenetrating one another in ordinary familiar 4D space-time. This marks an important step in demystifying QT - not least because it implies that QT can fit into the one here-and-now universe.

Identical Particle Interchange

W-state, in general, is a richly structured ontology. What has been presented thus far, in the theoretical minimum, are the opposite extremes. Eq. 15 encompasses the kinematic thread structure of single quantons, which is the lowest level of W-state structure, whereas the union of distinguishable quanton types in Eq. 16 represents the highest level of hierarchical structure.

Spin and identical particle interchange (IPI) represent intermediate levels of structure in W-state ontology, which have not yet been introduced and will be deferred until after the theoretical minimum. Whereas dissimilar quanton types can be treated simply as a set-theoretic union (bag), IPI involves *tight superpositions* of even- and odd-order permutations of ordered combinations of quantons of the same type. The realist treatment of spin and IPI entails introduction of elaborate new W-state structural concepts, which would strain the scope of the theoretical minimum.

2.2.5.2 Local Wavefunction of the Universe

Eq. 16 represents the totality of matter-energy, constructible from the RQF in Regime 1, that is present at point \underline{x} . Some quantons have greater presence there than others, based on amplitudinal weight. In general, it can be expected that there will be a roll-off of weights, such that only a small finite number of quantons will have appreciable weight at most points. The roll-off can be visualized as much like the singular values of a matrix.

“Wavefunction of the universe” (WFotU) is a grandiose term borrowed from the early period (1950’s) of quantum cosmology, but local WFotU - or, more properly, “the wavefunction of the universe, as it exists locally” - is a simple and meaningful concept. It matters for two reasons:

- The local WFotU *alone* is informationally sufficient to shape and drive the local W-state dynamics.
- The local WFotU determines the inertial frame locally tangent to the rest manifold, \mathcal{M} , at \underline{x} .

2.2.5.3 Local Rest Frame

Momentum Nullification

The local rest frame is that in which the local WFotU has net momentum zero, *viz.*,

$$\sum_n \int \left| \tilde{\psi}_n(\underline{k}, \underline{x}) \right| \underline{k} d\underline{k} = \underline{0} \quad (17)$$

in which the summation (n) is over the quanton types in Eq. 16 and \underline{k} is the wavenumber 3-vector obtained from the 4-vector \underline{k} in the local rest frame.

The validity of Eq. 17 hinges on: (i) the existence of at least one inertial frame satisfying the criterion, and (ii) the uniqueness of any such frame. The existence of a rest frame is guaranteed if all the quanton components are subluminal (*i.e.*, governed by Eq. 6 with $m > 0$), a condition definitely satisfied by quarks and leptons. The assurance analysis is somewhat more nuanced for photons and neutrinos, which do not have rest frames of their

own. In combination with massive quantons, however, a unique rest frame can be expected to be guaranteed under most circumstances.

The ultimate and most important criterion that the local rest frame must satisfy is that it be relativistically invariant. That is, any two observers inspecting the local WFotU, regardless of their motion relative to it, must agree as to whether any two points are simultaneous in the frame.

Voronoi Cell Extension to Vacuum

Eq. 17 is most easily satisfied in matter-rich settings, in which at least one quanton has appreciable presence. In vacuum regions, the question is more complicated. No quanton has strong presence absolutely, but momentum nullification depends only on the relative strengths of amplitudinal weights, even when they are tiny. By that reasoning, it follows that the local rest frame in vacuum is that of the nearest neighboring aggregation of matter (*e.g.*, a solitary gas atom).

To the gas atom, the rest manifold, \mathcal{M} , in its vicinity coincides with its own rest frame. The argumentation further indicates that \mathcal{M} is flat out across an extended region, which is the Voronoi cell enveloping the atom, *i.e.*, that region of space closer to it than to any other atom. The boundaries of the cell are surfaces on which two (or more) nearest neighbors are equidistant. At those boundaries, there is a thin transition region across which the amplitudinal weights of the neighbors are competitive.

2.2.5.4 Rest Manifold Emergence

The rest manifold, \mathcal{M} , emerges, in effect, as a crazy quilt of Voronoi cells, extending across the entire universe as a single big continuous 3D spatial slab. In diffusely gaseous regions, the Voronoi patchwork description holds quite literally, but not so much in regions of condensed matter, where multiple quantons with different velocities are competitive in the influence they exert.

Rest Manifold Criteria

The ultimate and most important criteria that the rest manifold, as a global geometric entity, must satisfy are two-fold:

- **Relativistic invariance:** Any two observers, anywhere in the observable universe, will agree on whether any two points are on the same rest manifold.
- **Global hyperbolicity:** Any two points on \mathcal{M} are guaranteed to be space-like separated.

Both criteria are crucial for establishing that rest manifolds can serve as substrates for non-local mediation of entanglement and cohesion effects within quantum systems. It is asserted (but not yet proven) that global hyperbolicity holds up to the Regime 5 limit of QG.

Foliation

Rest manifolds are instantaneous “snapshots” of the universe. They are conceptually conterminous with Barbour’s Nows [1]. Collectively, the rest manifolds form a single universal stack. Parametrization of the spacings between snapshots furnishes a qualitative notion of cosmic time⁵.

The global WFotU, in the full grandiose sense of the term, is the patchwork of local WFotU’s, restricted to a single rest manifold. Just as the local WFotU suffices to determine the PDF governing local W-state evolution, the global PDF suffices to determine the PDF governing global W-state evolution (including non-local correlations).

2.2.5.5 Interim Summary

This point marks the completed development of W-state, for purposes of the theoretical minimum. It has brought to light three distinctly non-classical characteristics of W-state:

⁵Contrary to prevalent sentiment in cosmology, which holds that time is non-existent.

- **Relational ontology**
- **Ontic primacy on the joint domain** (distinctly characteristic of wave-stuff)
- **Multi-situationality** (at the heart of ontic uncertainty)

It has further been shown how rest manifolds emerge from the quantum constitution of matter-energy, which is the basis for establishing that they are observer-independent and therefore not arbitrary.

2.3 Theoretical Minimum of P-state

This section is dedicated to answering the following key questions:

- How can the availability of rest manifolds, as global Lorentz-invariant geometric structures emergent from W-state, be used to mediate entanglement phenomenology evident in the evolution of W-state?
- How can P-state, as a global informational state resident on the manifolds but sealed off in a separate ontic domain of its own, enable weak non-locality to be effected mechanistically?

2.3.1 The Physical Origin of Measurement Processes

Entanglement phenomenology only becomes apparent after having performed measurements in experiments. Were quantum physics purely unitary and truly governed only by Rule 1, there would be no such thing as measurement processes and no observations of entanglement phenomenology. It is therefore appropriate, at this stage, to say something about what measurement processes *are* physically and how they amount to fundamental departures from unitary dynamics. Simply put, a deeper understanding of Rule 2 is needed now.

2.3.1.1 Historical Confusion about Measurement

The RQF maintains that the split dynamics (*i.e.*, coexistence of Rule 1 and Rule 2) is a real feature of Nature. The distinct and opposite natures of the two, intuitively, does not seem terribly hard to fathom: Unitary evolution, when it happens, is smooth, continuous, deterministic, conservative, reversible, and akin to laminar fluid flow or adiabatic gas expansion. Measurement processes are much the opposite: rough, turbulent, fitful, dissipative, non-deterministic, non-conservative, and irreversible. Two historical factors have impeded acceptance and recognition of this straightforward contrast.

Instrumentalist Bias

As was briefly noted in Sec. 2.1.2.3, instrumentalist bias historically skewed and distorted the understanding of measurement processes and Rule 2, giving the impression that it is something that *only* occurs in physics laboratories in the presence of physicists. Contrived experimental interventions (CEI), however, represent only a very special and rarefied class of measurement processes. They are an important and noteworthy class in that they are highly amenable to idealized abstraction and tractable mathematical analysis, but they are not at all the whole story of measurement processes in the quantum realm.

Obfuscation of Rule 2

Straightforward intuitive acceptance and understanding of Rule 2 has also been impeded and stymied by the two dominant schools of the quantum establishment. Both have strived to maximize the usage of Rule 1 formalism, yet have obfuscated invocation of the Born Rule:

- **Copenhagen:** Time-dependent perturbation theory (TDPT) is the staple tool of the trade to predict average longevities of meta-stable states (*e.g.*, excited atomic electrons, radioactive nuclei), using the Fermi Golden Rule. However, it improperly overextends the unitary Hamiltonian formalism, applying it to what are fundamentally non-conservative irreversible processes. It is forced to invoke the Born Rule to convert time-varying basis function coefficients in the unitarily evolving wavefunction into what can be interpreted as transition rates.

- **Many Worlds:** MW, like TDPT, ostensibly strives to be Rule 1 only, but unitary dynamics has no built-in mechanism to trigger bifurcation processes, through which daughter universes are created. It is forced to invoke the equivalent of the Born Rule to account for the phenomenology that any observer, navigating a sequence of stints in here-and-now universes, actually witnesses.

Decoherence

It took many decades - not until well into the second half of the 20th century - before the term *decoherence* caught on. It is often cloaked in formalism and jargon, but the basic concept is extremely simple and intuitive. Friction and entropy increase, as we experience them in everyday life, are simply decoherence writ large.

That is not the only connection between friction and quantum physics. It is noted that the Principle of Least Action is not all-encompassing: in classical mechanics because of friction, and in QT because of Rule 2. The common scope limitation is no accident.

2.3.1.2 Local Unease in the Wavefunction

The RQF takes a radically different view toward Rule 2 than standard QT.

It was noted in Sec. 2.2.5.2 that the local WFotU alone is informationally sufficient to shape and drive the local W-state dynamics. That readily gives telling clues about why dynamics can be Rule 1-like or Rule 2-like. The local WFotU is a cross-roads at which multiple quantons collocate. Great variation in masses, velocities, and interaction energies is possible. The assembled quantons may sometimes “sit well” together, in which case the ensuing evolution tends to be gentle, laminar, and predictable (*i.e.*, unitary). If, on the other hand, the assemblage is uncomfortable and disharmonious, the ensuing evolution may be rough, fitful, and unpredictable.

In general, the local WFotU determines a PDF governing the local W-state evolution, as was noted in Sec. 2.2.5.4. A harmonious WFotU yields a delta-function PDF, resulting in deterministic unitary evolution, whereas a disharmonious WFotU yields a non-delta PDF.

This simple understanding of measurement processes, as having to do with localized energy concentrations, makes perfect sense in the CEI context. A particle slamming into a detector, quite obviously, does exemplify an abnormally high concentration of energy.

2.3.1.3 Zitterbewegung

Even in the ground state and with just one quanton, there is still unease, because quantons have self-energy. $E = mc^2$ fundamentally does not sit well with unitarity.

That points to a telltale indicator that cropped up seemingly as a curio in the Dirac equation. It was brushed off and largely forgotten as footnote. It was treated as noise (figuratively and literally), but the founders should have treated it as signal. Just as singularities were taken as a sign of fundamental limitations in the scope of GR, zitterbewegung (zbw) should have been regarded similarly as an indication of scope limitation for unitary dynamics in QT.

zbw arises as a high-frequency oscillation (“jitter”) effect in the wavefunction solutions, at the pair-production threshold energy of $2mc^2$. It can be regarded, informally, as the revolt provoked by attempting to squeeze the relativistic electron into a unitary dynamics straightjacket.

The failure to heed zbw was a fateful methodological error that set quantum pedagogy backwards. The excessive focus on non-relativistic QM sweeps zbw under the rug and incubates the insidious impression that all is well in unitary dynamics.

The RQF recognizes zbw as a powerful concept that must be plucked out of obscurity and brought forth to front-and-center importance as the fundamental source of unease (self-energy). In the narrative that follows, it is the answer to the basic question of *why* measurement processes are occurring in the first place.

2.3.2 Information-Theoretic Narrative

2.3.2.1 Allegory of Spy Fiction

The narrative tale of entanglement phenomenology and how it is implemented mechanistically can be told through the allegorical lens of spy fiction, based on the 1965 Le Carré novel and film *The Spy Who Came in from the Cold*. It effectively illustrates the clandestine information-theoretic relationships between the W- and P-domains needed to uphold the illusion of locality in W-state dynamics. The protagonists:

- **Leamas:** the agent of local physics (AoLP) in the W-domain;
- **Mundt:** The central authority and omniscient mastermind within the P-domain;
- **Control:** Nature itself, as the architect of the W- and P-domain duality;
- **Riemeck:** the covert channels (one each way) that interconnect the W- and P-domains. Leamas is completely ignorant of their existence, but Mundt is entirely cognizant.

2.3.2.2 The Agent of Local Physics

Leamas' utilitarian goal is to minimize his disharmony with the WFotU, as it exists locally. As far as he can tell, the optimal way of doing that is to follow the prescription of local dynamic law. His task is to time-march the local WFotU forward to the next rest manifold incrementally ahead. How does he do that operationally? He has complete knowledge of the local WFotU, which gives him the complete information to determine the PDF governing its evolution to the next manifold.

Leamas needs a random number generator (RNG) to obtain a *pointer*, which he uses to draw a random sample from the PDF, which determines his actual step forward. Control has instructed Leamas to draw his pointers from an RNG recessed into the ontic wall between the W- and P-domains: “My dear Alec, I can assure you that it is a perfectly innocuous accommodation address. Run every imaginable statistical test, and the pointer distribution will be perfectly uniformly distributed on the unit interval.”

Indeed, Leamas cannot gainsay Control by any instrumental means. This is the illusion of locality. The no-signaling stricture of SR is all about upholding the illusion.

2.3.2.3 Global Situational Awareness in the P-domain

Unbeknownst to Leamas, the RNG is bugged. Like the characters in *The Lives of Others*, every detail of the local WFotU that Leamas oversees is being captured and tunneled through the ontic wall to the P-domain, where it is received by a different local agent (Riemeck), called a *mapper*.

Natural computation in the P-domain is implemented as a distributed computing paradigm akin to MapReduce. The mappers forward their acquired data to Mundt, the *reducer*, who acquires full knowledge of the WFotU globally across the entire rest manifold.

2.3.2.4 The P-state Mandate

Control allows Mundt to use the information acquired globally across the WFotU only to construct a multivariate PDF. Mundt's utilitarian goal is to minimize unease globally on the rest manifold, as best he can within Control's mandate.

For simplicity, it can be stipulated, without loss of generality, that the PDF is of a *hypercubic* design, such that sampling any single dimension (*i.e.*, integrating over all the others) yields a uniform distribution. With the help of the mappers (by means described in the next section), the reducer draws a random sample from the PDF, which in general is highly unfactorizable. The reducer returns the vector components of the drawn sample value, called *pseudo-innovations*, to the mappers.

2.3.2.5 Coordinated Influence over the W-state

The mapper (Riemeck) delivers the vector component (a pseudo-innovation) into Leamas' RNG through the backdoor that faces into the buffer zone in the ontic wall.

2.3.3 Execution of the Unfactorizable PDF

The spy narrative completely describes the clandestine information flows and mechanistic framework through which weak non-locality is enforced. The illusion of locality is guaranteed to be upheld, provided that the PDF is hypercubic. Assuming the availability of such a PDF, the main question that remains is how a random sample can be drawn, in unbiased fashion, from it.

2.3.3.1 Natural Computation Algorithm

We consider a simplified computing scenario consisting of finitely many (N) measurement sites (*i.e.*, a Leamas-Riemeck pair of agents on opposite sides of the wall) on \mathcal{M} . The pseudo-innovations are to be drawn from an N -dimensional PDF, *viz.*,

$$P(\mu_1, \mu_2, \dots, \mu_N) \quad (18)$$

The hypercubic property is such that integration over all but one dimension yields a uniform distribution, *e.g.*,

$$\int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} P(\mu_1, \mu'_2, \dots, \mu'_N) d\mu'_N \cdots d\mu'_2 = 1 \quad (19)$$

Note that the result in Eq. 19 is independent of (uniform on) the lone unintegrated variate μ_1 . The same holds for the other variates.

We envisage a distributed MapReduce-like computing architecture, in which the reducer makes the PDF visible to the mappers, which do the computational work of computing the pseudo-innovations.

Gambit Arbitration

To draw a random sample from the PDF, N uniformly distributed numbers (r_1, \dots, r_N), called *pointers*, are needed, along with a specified order in which the dimensions will be indexed. The mappers 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 mapper 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 mapper ascertains its rank in the lineup by comparing its own gambit to those of its peers⁶.

Computation of the Pseudo-Innovations

After gambit arbitration, the mappers perform a sequence of definite integral evaluations to derive the pseudo-innovations:

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

$$\int_{-\infty}^{\mu_1} \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} P(\mu'_1, \mu'_2, \dots, \mu'_N) d\mu'_N \cdots d\mu'_2 d\mu'_1 = r_1 \quad (20)$$

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

$$\int_{-\infty}^{\mu_2} \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} P(\mu_1, \mu'_2, \dots, \mu'_N) d\mu'_N \cdots d\mu'_3 d\mu'_2 = r_2 \quad (21)$$

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

⁶Gambit arbitration is conceptually no different from what CSMA/CD does to mitigate network traffic collisions.

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

$$\int_{-\infty}^{\mu_3} \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} P(\mu_1, \mu_2, \mu'_3, \dots, \mu'_N) d\mu'_N \cdots d\mu'_3 = r_3 \quad (22)$$

- ...

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

$$\int_{-\infty}^{\mu_N} P(\mu_1, \dots, \mu_{N-1}, \mu'_N) d\mu'_N = r_N \quad (23)$$

The pseudo-innovations (μ_1, \dots, μ_N) are unbiased draws from the PDF, provided that the gambits and pointers are *true innovations* drawn from genuine RNG's inside the P-domain. If the PDF were factorizable, the pseudo-innovations would be genuine and untainted (*i.e.*, uncorrelated with anything else).

2.3.3.2 Absolute Randomness

It is noted and emphasized that *absolute randomness* of the kind envisaged in traditional QT is vindicated by the RQF. It is not merely a matter of philosophical taste vis-à-vis determinism; it is mathematically demonstrable of being the *only* way to implement weak non-locality while upholding the no-signaling stricture of SR. Alternatively stated, the phenomenology of weak non-locality proves that Nature is fundamentally non-deterministic (*i.e.*, powered by true innovation).

2.3.3.3 Natural Computation

The mechanistic model of weak non-locality 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 of weak non-locality to produce measurement outcomes in individual systems that conform statistically to a specified arbitrary unfactorizable PDF.

Natural computation is a metaphor for what Nature has to do to make it happen, obviously without human computing technology. Somehow, Nature accomplishes the feat. In natural computation, the mappers are spatially separated, but space does not act as a barrier. They somehow cooperate superluminally.

2.3.3.4 Updating of P-state

The remaining question that has not been answered is how the reducer obtains or computes the P-state (which *is* the PDF) in the first place.

Bayesian Updating

A general statement about the P-state dynamics is that it is governed by a Bayesian updating rule of the form:

$$P(\tau + \Delta\tau) = \mathcal{Q}(P(\tau), W(\tau)) \quad (24)$$

in which τ is global time, W is the global WFotU, and P is the P-state. \mathcal{Q} is the functional form (logic) of the updating rule, which draws upon the reducer's global situational awareness of the WFotU. How Nature "knows" what \mathcal{Q} should be is yet another ineffable marvel of natural computing.

QBism

Eq. 24 can be regarded as an ontification of quantum Bayesianism (QBism), which is a surprising and ironic result. It portrays Bayesian updating as a physical process in Nature, not as an epistemic process as we usually think of it. Whereas QBism envisages its epistemic application in the W-domain, the RQF finds ontic application for it in the P-domain.

2.3.3.5 Obviation of Tachyons

The RQF puts a stake through the heart of tachyons, which are a historical artifact of attempting to devise a non-local correlation mechanism consisting of physical state (like W-state) and thus governed by the kinematic and no-signaling criteria of SR. By separating and ascribing altogether different ontic properties to the W- and P-domains, the RQF completely circumvents the trap of superluminal signaling and eliminates need for tachyons.

2.3.4 RQF Analysis of the EPR Experiment

We conclude the theoretical minimum with an analysis of the Einstein-Podolsky-Rosen (EPR) thought experiment, which historically (1935) first brought entanglement phenomenology to attention and identified the need for P-state as a global coordination mechanism missing from the wavefunction-only formalism.

2.3.4.1 Experimental Setting

Photonic Source

At the center of the experiment is a two-photon source, such as the calcium atom in the Aspect experiment. The atom is initially excited and undergoes a two-step radiative drop to the ground state, emitting two photons in the process.

The photonic W-states are a bosonic combination of two thin spherically symmetric shells centered around the atom. The spherical symmetry indicates that the photonic W-state is in an objectively real state of directional indefiniteness, indifferent to where Alice or Bob may be lying in wait with their detectors.

Alice and Bob

Alice is situated with her detector, some distance apart in the laboratory from the source. Bob is situated at a diametrically opposite location.

There are now four agents in the plot: Alice-W and Bob-W are the agents of local physics. Alice-W consists of a polarization filter, whose preferred axis is at some definite angular orientation. Bob-W also has a polarization filter, whose angle relative to that of Alice-W is some definite value, θ .

As a single photon comes the way of Alice-W, either of two possibilities occurs. One is that the photon passes through the filter, but with transformed W-state of definite polarization. The other possibility is that the photon is blocked by the filter; the photonic W-state is absorbed and ceases to exist as such. The filter absorbs the momentum and energy imparted by the photon, which is converted to heat.

Alice-P and Bob-P are the mapper counterparts in the P-domain. Each is aware of the local W-state situation, which is reported to the central authority (reducer). Each P-agent hands it W-counterpart a pseudo-innovation, which dictates the course that the local W-physics takes.

Data Acquisition and Analysis

Many runs of the experiment are performed. In each run, a pair of photons is emitted, and Alice-W and Bob-W record the outcome facts. After many runs and comparison of their data afterwards, they discover violation of the CHSH inequalities. How can Nature make that happen?

2.3.4.2 Case 1: Alice Closer to the Source than Bob

We consider two variants of the experiment. In the first, Alice is closer to the photonic source than Bob. In this scenario, Alice-B hands Alice-W a pseudo-innovation that is, in actuality, a genuine innovation, because Alice is the lone uncontested measurement site. It is just as if Alice had drawn on her own from an untainted RNG, unattached to the ontic wall.

A random outcome is established for Alice-W. That outcome shapes the updating of the P-state, which will constrain Bob-W to realize the opposite outcome, when the other photon eventually reaches him. The W-state of Bob's photon, which is still in flight, is not instantaneously affected in the wake of Alice's detection event. The

W-state itself is still spherically symmetric and directionally indefinite. However, the P-state update has bearing on what will eventually become of it:

- **Directionality:** The photonic W-state emanating from the atom is a bosonic combination of two mutually entangled photons. The entanglement obligations are two-fold: (i) net-zero translational momentum, and (ii) net-zero rotational momentum. Both impose P-state constraints that shape the eventual fate of Bob's photon, after Alice's detection event. It follows from the conservation of translational momentum obligation that Bob's photonic W-state is *effectively* (but not actually) collapsed from a spherically symmetric shell to a pencil beam. That is, it henceforth stands a chance of being detected only at positions diametrically opposite Alice's location (as Bob actually is in the laboratory). The collapse to pencil beam can be regarded as the epistemic QBism update; an observer cognizant of Alice's outcome would learn that Bob's photon is now subject to this known fate.
- **Detection Outcome:** It follows from the conservation of rotational momentum (spin) obligation that the local PDF governing the outcome that Bob realizes depends on the outcome that Alice realized, in the individual run. The probability of his realizing the same outcome as Alice is $\cos^2 \theta$, where θ is the angular difference in their filter angles.

2.3.4.3 Case 2: Alice and Bob Equidistant from the Source

The case of two detectors equidistant from the source is only slightly more complicated, in that it involves gambit arbitration. In this case, Alice's and Bob's detection events are simultaneous; they both lie on a common rest manifold.

Alice-B and Bob-B effect the tie-breaker by generating a pair of gambit values. The one drawing the higher gambit gets first crack to have its outcome determined. In effect, the P-agent drawing the higher gambit takes the role of Alice in Case 1.

2.3.4.4 Entanglement Phenomenology within Single Quantons

The EPR analysis might give the impression that it has only to do with entanglement effects among two or more quantons, but that is not at all the case. It applies equally to what happens within single quantons, such as in the one- or two-slit experiment or in a Mach-Zehnder interferometer. In both cases, particle holism (*i.e.*, the fact that a particle detection occurs in only one place) is a manifestation of non-local entanglement phenomenology.

In the Mach-Zehnder interferometer, photonic W-state encounters a beam splitter, which divides the W-state into two spatially separated lumps, which can properly be regarded as half-photons. When a half-photon encounters a detector, one of two outcomes is possible:

- **Positive Detection:** When the W-state of a half-photon encounters a detector (while the other half-photon is still in flight), the gambit arbitration is waived, but the pointer value generated by the mapper at the site determines whether a positive or negative detection outcome materializes. If a positive detection outcome occurs, the half-photon W-state instantaneously becomes whole, and the detector experiences absorption of a whole photon. The P-state coordination does not instantaneously change the W-state of the other half-photon, but it effectively neuters it by rendering it a ghost wave. It is assured of registering negative when it is eventually intercepted by a detector.
- **Negative Detection:** The other possible outcome for the first half-photon is a negative detection. In this case, the W-state completely dies on the spot, with absolutely no locally observable effect. This is known as a *Renninger non-measurement event*. The P-state coordination effectively renders the W-state of the other half-photon more potent, assuring that it will eventually register positive. The Renninger death dramatically underscores the non-local rearrangements of W-state through which the P-state enforces conservation laws globally, but not locally, amidst measurement processes affecting any parts of the W-state of quantons.

In classical physics, the notion that particles hold together is taken for granted. In the quantum realm, however, particle-stuff (*i.e.*, hard billiard balls) no longer exists. Particle holism is instead cohesion emergent from within wave-stuff and is thus as much a part of quantum strangeness as the CHSH violations.

2.4 Rehabilitation of Standard Quantum Theory

2.4.1 Free Quantum Motion

2.4.1.1 The Big Bounce Solution

The non-relativistic quantum textbook (*e.g.*, [17]) considers the problem of a free quantum, initialized at time $t = 0$ as a Gaussian wavepacket in one dimension, *viz.*,

$$\psi(x, 0) \propto e^{-x^2/2\sigma^2} \quad (25)$$

in which σ is the initial width (root-variance). Eq. 25 is an instantaneous snapshot of a superposition of rigid waves (infinitely long straight threads), which evolve over time to yield an expanding wavepacket, *viz.*,

$$\psi(x, t) \propto e^{-x^2/2\Sigma^2(t)} \quad (26)$$

in which

$$\Sigma(t) = \sigma \left[1 + \left(\frac{\hbar t}{m\sigma^2} \right)^2 \right]^{1/2} \quad (27)$$

is the root-variance at future time $t \geq 0$.

Perplexity

The result in Eq. 27 is peculiar and troubling, for three reasons. (*i*) First is the mere fact that the packet width is not time-invariant. One would intuitively expect a free quanton, unbuffered by any external forces, to be static or at least exhibit some form of steady-state internal dynamism, yet traditional QT says otherwise. (*ii*) Second is that the variance, Σ^2 , grows *quadratically* with time, whereas it grows linearly in diffusion (*e.g.*, random walk) processes. (*iii*) But it is even worse than that. It is noted that the solution in Eq. 27 is a symmetric function of t about time zero, which amounts to a Big Bounce! The Gaussian initialization in Eq. 25 turns out to be a hand-crafted snapshot at the center of the bounce. At $t < 0$, the packet is shrinking, rather than expanding.

2.4.1.2 Zitterbewegung in Non-Relativistic Quantum Mechanics

The RQF takes an altogether different view toward the dynamic behavior of the free quanton. The Big Bounce solution underscores the folly of rigid wave mechanics and the tormented consequences of sweeping zbw under the rug and pretending that it has no role in non-relativistic QM.

Random Walk of Free Quantum

The RQF holds that the free quanton is continually buffeted by micro-measurement kicks to the left or right. The result is a random walk motion of the packet center. The packet width is non-zero and on the order of the Compton wavelength (\hbar/mc), but is constant over time (as an ergodic distribution). The non-zeroness of the packet width is zero-point multi-situationality, which is an inherent feature of W-state in the quantum realm. It signifies a stiff limit on the compressibility of the W-state.

The micro-measurement rate is $\omega = E/\hbar$, where E is as given in Eq. 8 and consists of rest and kinetic parts, *viz.*,

$$E = mc^2 + K \quad (28)$$

The agitation is a mixture of kicks owing to zbw (at a contribution rate proportional to the rest energy) and the thermal environment (at a contribution rate proportional to the kinetic energy, K , and the temperature, T). The variance growth rate characterizing the random walk is equal to $\ell^2\omega$, where ℓ is the step size. With the estimate $\ell = \hbar/mc$, it follows that the growth rate at $T = 0$, which arises purely from zbw, is equal to $D = \hbar/m$. The variance growth rate increases linearly with temperature, *viz.*,

$$D = \hbar/m \left(1 + \frac{K}{mc^2} \right) \quad (29)$$

in which the kinetic energy, K , is on the order of the thermal energy, $k_B T$.

2.4.1.3 Ontic Uncertainty Principle

The ontic uncertainty principle pertains to the product of Δx , which arises from spatial multi-situationality (wide-threadedness) inherent in the W-state, and Δp , which arises from internal dynamism. For the free quanton, Δx equates to the Compton wavelength, \hbar/mc , and Δp is on the order of mc . It follows that the product is on the order of \hbar , as conventionally required.

Δx is temperature-independent, as individual micro-measurements, regardless of their frequency, collapse the W-state to the smallest size allowed. Δp , on the other hand, increases with temperature, as the momentum is functionally related to K .

2.4.1.4 Traditional Instrumentalist Understanding of HUP

The ontic uncertainty principle is very different from the traditional instrumentalist understanding of HUP, both in Δx and Δp . The traditional understanding is based on rigid wave mechanics and conventional Fourier analysis of wave packets. In HUP, Δx is based on spatial compactness achievable with superpositions of rigid waves. In the RQF, the meaning of Δx and the reason for its non-zerosness are entirely different. The same holds for $\Delta k = \Delta p/\hbar$, whose non-zerosness in HUP stems from the Fourier trade-off required to achieve spatial compactness. In the RQF, the meaning of Δk and the reason for its non-zerosness (*i.e.*, arising from internal dynamism inherent in thread structure) are entirely different from HUP.

2.4.2 Core Formalism

We now proceed to reconstruct the core mathematical machinery of traditional QT, based on the physical ontology and principles of the RQF.

2.4.2.1 Reinstatement of Classical Mechanics

In Sec. 2.2.4.3, the concept of flexible long threads, with dynamics of their own, was mentioned. We now proceed to address and develop that in detail. The introduction of thread dynamics amounts to nothing less than a wholesale reinstatement of classical mechanics and its integration into W-state dynamics. In fact, classical mechanics running the hood is what powers Rule 1 dynamics (*i.e.*, where and when it applies, within islands of order) in the RQF.

Thread Dynamics

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

$$L(\underline{x}, \underline{\dot{x}}) \tag{30}$$

in which \underline{x} and $\underline{\dot{x}}$ 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) that prevail within the local WFotU.

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

$$\underline{\dot{p}} = \underline{F} \tag{31}$$

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

$$\underline{p} \equiv \frac{\partial L}{\partial \underline{\dot{x}}} \tag{32}$$

and \underline{F} is the force acting on the thread, *viz.*,

$$\underline{F} \equiv \frac{\partial L}{\partial \underline{x}} \tag{33}$$

The Hamiltonian, which is the Legendre transform of the Lagrangian, *viz.*,

$$H \equiv \underline{p} \cdot \underline{\dot{x}} - L \tag{34}$$

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

$$\dot{\underline{x}} = \frac{\partial H}{\partial \underline{p}} \quad (35a)$$

$$\dot{\underline{p}} = -\frac{\partial H}{\partial \underline{x}} \quad (35b)$$

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

Thread Phase

Tangent to any point, \underline{x} , on a thread is the QWE corresponding to (*i.e.*, inferred by analytic continuation of) $\tilde{\psi}(\underline{k}, \underline{x})$. 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.*,

$$S \equiv \int_{\underline{x}_A}^{\underline{x}_B} L(\underline{x}, \dot{\underline{x}}) dt \quad (36)$$

in which dt denotes increments of proper thread time.

Absoluteness of the Quantum Lagrangian

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. 36 must be absolute, whereas in classical mechanics, the Lagrangian is indeterminate to within an arbitrary additive constant.

Feynman Path Integration

Eq. 36 relates directly to Feynman paths, which are subject only to the restriction⁷ of being world lines, any two points on which are time-like separated. To evaluate an arbitrary path integral, the RQF readily provides a procedural recipe:

- The 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. 36.
- In transferring from one thread segment to the next at any waypoint, the integration is adjusted by the phase difference between the incoming and outgoing threads, which is determinate by virtue of their local interference (Sec. 2.2.3.5).

It is noted that on all intervals of the path discretization, the phase integration “piggybacks” on a short thread, which the RQF holds to be physically real in fashion determined by underlying classical mechanics. Summation over all of Feynman’s crazy paths is therefore unnecessary and superfluous. Feynman path integration becomes subsumed under classical mechanics.

2.4.2.2 Causal Structure of W-state Dynamics

To simulate the dynamic evolution of W-state, $\tilde{\psi}(\underline{k}, \underline{x})$ must be initialized for all \underline{k} and \underline{x} on a Cauchy manifold, \mathcal{M} (which need not be a rest manifold). Assuming linear unitary dynamics, the W-state at all points causally downstream of \mathcal{M} is then obtained as:

$$\tilde{\psi}(\underline{k}, \underline{x}) = \int_{\mathcal{M}} G(\underline{k}, \underline{x}, \underline{k}', \underline{x}') \tilde{\psi}(\underline{k}', \underline{x}') d\underline{k}' d\underline{x}' \quad (37)$$

⁷Popular descriptions and illustrations often overstate the “crazy” character of Feynman paths.

in which G denotes a Green's function, which is a W-state propagator. Eq. 37 is centrally important to W-state dynamics and provides the basis for speaking of relationships among $\tilde{\psi}$ values at time-like separated points. Assuming linear unitary dynamics only between measurement events, G captures completely the physics that governs the evolution of the quanton W-state until the next measurement event.

2.4.2.3 Hilbert Space

Eq. 37 is recognizable as an integral form of the Schrödinger equation. To bring forth the Schrödinger equation to recognizable form, however, the topic of Hilbert space and how it finds expression in the RQF must now be addressed.

L^2 Space Derivation from W-state

Eq. 15 provides the formulaic means of deriving the wavefunction, a quantity ontically primary on the space-time domain, from W-state. Consider now the restriction of $\Psi(\underline{x})$ to points \underline{x} on a rest manifold, \mathcal{M} . The RQF now stipulates the following axiom about W-state structure: The set of physically realizable W-state configurations, globally across \mathcal{M} for a single-quanton system, is an L^2 space.

With conventional functions ontically primary on one domain, L^2 signifies square-integrable functions and orthogonality (*e.g.*, vanishing of inner products of different functions in a basis set). In conventional QT, the significance of square-integrability is associated with the probabilistic interpretation of the wavefunction through the Born Rule. In RQF, L^2 space provides a gateway to Hilbert space, which enables the core formalism of standard QT to be reproduced.

L^2 on Relational Ontology

The L^2 space of W-state configurations is spanned by a countable set of equivalence classes $\{\mathcal{E}_1, \mathcal{E}_2, \dots\}$. Each \mathcal{E}_i is a set of square-integrable referenced mappings, any two of which are the same modulo a non-zero multiplicative constant. For $i \neq j$, the equivalence classes \mathcal{E}_i and \mathcal{E}_j are mutually orthogonal in that the inner product of any referenced mapping in \mathcal{E}_i and any referenced mapping in \mathcal{E}_j is zero, in the usual sense.

L^2 Gateway to Hilbert Space

The gateway from L^2 to Hilbert (ℓ^2) space is the Riesz-Fischer theorem, which establishes the canonical isometric isomorphism between the two. This linkage provides direct answer to the question of what a Hilbert vector, $|\psi\rangle$, often regarded as a purely abstract formal symbol, means in meat-and-potatoes physical terms: It represents a particular form of W-state slice on a rest manifold. More simply put, it is a W-state snapshot of a quanton.

2.4.2.4 Schrödinger Equation

The evolution of the W-state slice, $|\psi\rangle$, over a succession of rest manifolds is governed by the Schrödinger equation, which can now be expressed in its familiar form, *viz.*,

$$\frac{d}{dt} |\psi\rangle = -i/\hbar \cdot \mathcal{H} |\psi\rangle \quad (38)$$

in which \mathcal{H} is the Hamiltonian in Heisenberg matrix form. Eq. 38 is the reification of matrix mechanics. The exponentiation of \mathcal{H} yields the propagator, G , just as in standard QT.

It is noted that the Hamiltonian, \mathcal{H} , is different from, but related to, the Hamiltonian, H , in Eqs. 34-35. The latter (H) is the “little Hamiltonian” of classical mechanics, whereas \mathcal{H} is the “big Hamiltonian” of standard QT. The little Hamiltonian is the more fundamental of the two. The big Hamiltonian can be derived from the little, just as the wavefunction can be derived from W-state, but derivation in the opposite direction is barred.

Historically, the Schrödinger equation was discovered through heuristic analogy to the Hamiltonian formulation of classical mechanics. The analogy, of course, proved pragmatically 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 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 propagator, 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. Indeed, the Copenhagen view implicitly regards the ontology (even if it does not call it that) as primarily particle-like.

2.4.2.5 Measurement Processes

Internally- and Externally-Triggered Measurement Processes

In the RQF, Rule 2 dynamics, which are held to be physically real and fundamentally distinct from Rule 1, are highly diverse. They are ubiquitous in Nature, with or without conscious observers. A useful way of visualizing the diversity is on a spectrum between internally- and externally-triggered. The variation depends on the degree of unease resulting from local energy concentration in the W-state, which includes all quantons that collocate (to varying degrees). Generally speaking, the greater the energy concentration (*e.g.*, resulting from collision), the more "externally-triggered" the departure from unitary dynamics can be said to be. Residual zero-point zbw in an isolated quanton exemplifies the internally-triggered end of the spectrum.

The terms "micro-measurement" and "macro-measurement" are roughly, but not precisely, associated with internally- and externally-triggered respectively. A macro-measurement occurs when the W-state of a microscopic quantum system, consisting of no more than a few quantons, encounters that of a macroscopic body, typically a measurement instrument.

Contrived Experimental Interventions

Contrived experimental interventions (CEI) are a very important class of macro-measurement processes. They are the central focus of traditional QT.

CEI's are amenable to highly idealized abstraction and simplification, which makes the formal analysis mathematically tractable. In a CEI, the entirety of the macro-measurement process transpires on a single rest manifold. The relevant aspects of the WFotU consists of two parts: (*i*) the pre-measurement W-state of the microscopic system, which can be represented by a Hilbert vector, and (*ii*) the global configuration of the W-state of the measuring instrument, which dictates the *type* of measurement process that will take place. In the conventional formalism, that translates to selection (by the experimenter) of a Hermitean operator (A) on the Hilbert space (or, equivalently stated, a particular basis spanning the space of W-state configurations on \mathcal{M}). The global PDF (P-state) is directly related to the *spectral measure* on A .

The global information-theoretic exchange, detailed in Sec. 2.3.2, can be simplified somewhat. The meticulously tailored design of the macroscopic intervention is such that the only probabilistic latitude available to the P-state is the discrete set of eigenspaces of A onto which the pre-measurement W-state can be projected.

Quantum Jumps

Because CEI's are concentrated entirely on a single rest manifold, it follows that the entire W-state can change discontinuously globally across the entire manifold. This is the reification and demystification of a *quantum jump*, much as Bohr originally envisaged.

The Anatomy of a Measurement Process

What really happens in a measurement process, such as in a Stern-Gerlach magnet? An inquisitive student wants to know. He once asked in lecture: "But how can you say that it's a meaningless question when the measurement occurs. It seems to me that it would be in the magnet apparatus, when they start to part company into two beams." The student becomes befuddled and sandbagged, because of what the lecturer has just told him: (*i*) There is no such thing as a "measurement event", because it is meaningless to ask when an atom gets measured.

(ii) It is not the job of QM to answer any question about an individual atom. QM is only about probabilities and prediction.” A snark chimes in: “Didn’t you know that?”

The RQF is more helpful:

- The atom gets “measured” not at a sharply defined instant, but rather, over a fuzzy transition width.
- In the mid-section of the magnetic guide, the atom is teetering on a knife edge of unstable equilibrium. This is where it enters a twilight zone.
- In the twilight zone, the atom gets up and down (and sideways) zbw kicks - the unavoidable quantum facts of life. It is agitated and unsettled, but it still a toss-up which way it will go.
- By chance, one direction gets the upper hand, and the P-state sees to it that the drift becomes self-amplifying. This is incipient beam divergence.
- Not long and the atom reaches a point of no return, exiting the twilight zone. A measurement outcome (up or down) has been decided.

Quantum statistical mechanics (QSM) enables the sequence of atoms in the beam to be simulated as an ergodic ensemble. It takes account of the field geometry in the magnetic guide, in conjunction with a decoherence model (zbw kicks, collisions with air molecules) to predict diffusion spread of the beam. The random walk model makes two falsifiable predictions: (i) Target hits in each of the clusters are normally distributed on the screen. (ii) The cluster area (Mahalanobis ellipse) is proportional to the distance from the magnet exit to the screen.

Just as a horse cannot be taught calculus, traditional QT, as the lecturer unwittingly acknowledged, is fundamentally ill-equipped to reckon with the student’s innocent question. That is because it was designed as an instrumentalist tool, forged in an information environment that was nowhere close to envisaging or supporting this kind of detailed elaboration of the microworld. The RQF has the benefit of a century of hindsight, not only empirical factual wealth, but also battle-hardening from experience with deep-set prejudices and groupthink.

2.4.2.6 Born Rule

Can the Born Rule be proved, as a mathematical theorem? To do so from truly first physical principles would be exceedingly difficult, as it would require deeper investigation of the premise, accepted axiomatically by traditional QT (and also by the RQF, at this stage of development), that a CEI translates to a choice among the eigenspaces of a Hermitean operator, A , that summarily characterizes the global W-state configuration of the measuring instrument. Within that confined scope, however, geometric argumentation implies that the Born Rule is mathematically the most parsimonious and compelling formulaic recipe for the measurement outcome probabilities.

Physical Axiom

CEI’s, in well-defined experimental settings for which they are suited, simplify to a Hilbert space of W-state configurations in ℓ^2 . The completeness of ℓ^2 justifies approximate analysis using a reduced-order Hilbert space of finite dimension, N . In the finitized space, the Hermitean operator, A , has $M \leq N$ eigenspaces with distinct eigenvalues. Some of the eigenspaces may be degenerate ($d_m > 1$). The eigenspaces span the finitized space, *viz.*,

$$\sum_{m=1}^M d_m = N \tag{39}$$

The M eigenspaces are henceforth treated on an equal footing. They can be regarded as geometric axes of an M -dimensional *uniquified Euclidean space*. We now set forth the following physical axiom: The combination of the pre-measurement W-state slice on the rest manifold and the stochastic processes that transpire in the P-domain maps to a normalized vector, $|v\rangle$, that is uniformly distributed on a unit sphere in the uniquified Euclidean space.

Forward Bayesian Problem Formulation

The supposition of a uniform probability distribution on the unit sphere in the unquified Euclidean space is steeped in physical assumption and simplification. It is far beyond the wherewithal of traditional QT to justify the supposition. The RQF, being well-grounded in physical ontology, in principle offers the means to investigate the question further, but that is far beyond the current introductory scope.

Once the supposition is accepted, however, it becomes a question, purely within the mathematical domain, of whether the Born Rule provides a well-justified formulaic recipe for the probability, $P(m|v)$, that answers the following question, which is posed as a *forward* Bayesian problem formulation: What is the probability that a vector, $|v\rangle$, drawn at random from a uniform distribution on the unit sphere, will collapse onto a given eigenspace, m ? The Born Rule holds that the forward probability is given by:

$$P(m|v) = \langle v | \mathbf{P}_m | v \rangle \quad (40)$$

in which \mathbf{P}_m denotes the projection operator from the finitized ℓ^2 space onto the m 'th eigenspace. From the completeness of ℓ^2 , it follows that:

$$\sum_{m=1}^M \langle v | \mathbf{P}_m | v \rangle = 1 \quad (41)$$

Reverse Bayesian Problem Formulation

Consider now the reverse Bayesian problem formulation: An eigenspace, m , is chosen first. The M eigenspaces are deemed equiprobable, and one is chosen at random. A point on the unit sphere is then drawn based on the reverse probability $\pi(v|m)$.

The first question is whether the reverse stochastic synthesis reproduces the uniform distribution on the unit sphere. It does, provided that the Bayes relation holds, *viz.*,

$$P(m|v) = \frac{\pi(v|m)}{\sum_m \pi(v|m)} \quad (42)$$

From Eqs. 40-42, it readily follows that the Born Rule is equivalent to the proposition that

$$\pi(v|m) = \langle v | \mathbf{P}_m | v \rangle \quad (43)$$

The remaining question now is whether the reverse probability in Eq. 43 can be justified on heuristic mathematical grounds more easily than the forward probability in Eq. 40.

Geometric Argumentation

The plausibility of Eq. 43 can indeed be justified by geometric argumentation in the unquified Euclidean space. Consider the set of concentric cylinders centered around the axis m , which has already been chosen. It is reasonable to assume that the subset of vectors, $|v\rangle$, on each cylinder is equiprobable. That is, $\pi(v|m)$ depends only on the cylinder on which $|v\rangle$ lies.

A quantitative expression for $\pi(v|m)$ is now at hand, based on geometric argument: $\pi(v|m)$ is equal to the proportion of area on the unit sphere that lies outside the cylinder containing $|v\rangle$. That proportion of area is equal to $\cos^2 \theta$, in which θ is the angle, in the Euclidean space, between $|v\rangle$ and the axis of the m 'th eigenspace. This is congruous with the conventional geometric interpretation of \mathbf{P}_m .

Interim Summary

This section has continued from the theoretical minimum to reproduce the core formalism of traditional QT, which is centrally focused on CEI's and Hilbert spaces. It has connected the core formalism to the physical ontology and dynamics of W- and P-state that underlies the CEI's. In building the connection, two additional physical axioms were introduced:

- **Physical premise of Hilbert space:** The set of W-state slices on rest manifolds is mathematically an L^2 space, which means that W-state (wave-stuff) is physically compact.

- **Physical premise of the Born Rule:** The combination of the pre-measurement W-state slice on the rest manifold and the stochastic processes that transpire in the P-domain maps to a normalized vector, v , that is uniformly distributed on a unit sphere in the unquified Euclidean space.

2.4.3 Elaboration of W-state Structure

What has been described thus far is an oversimplification of real quantons in the Standard Model. It has actually been describing “spinless electrons”, which, of course, are fictional beasts. This section introduces what was promised, but deferred, in Sec 2.2.5.1: a full reckoning with spin and identical particle interchange. Both introduce important new intermediate-level ontic structure in W-state.

2.4.3.1 Spin

In the RQF, spin is regarded as anisotropy inherent in the ontic structure of local W-state.

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, $\mathbf{R}(\hat{z}, \vartheta)$, to the W-state signifies an active transformation, 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.*,

$$\mathbf{R}(\hat{z}, \vartheta) \cdot \uparrow_{\hat{z}} = e^{is\vartheta} \cdot \uparrow_{\hat{z}} \quad (44)$$

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

$$\mathbf{R}(\hat{z}, \vartheta) \cdot \downarrow_{\hat{z}} = e^{-is\vartheta} \cdot \downarrow_{\hat{z}} \quad (45)$$

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

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.*,

$$\uparrow_{\hat{z}} + \downarrow_{\hat{z}} = \uparrow_{\hat{x}} \quad (46)$$

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.

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:

$$e^{is\vartheta} \cdot \uparrow_{\hat{z}} + e^{-is\vartheta} \cdot \downarrow_{\hat{z}} = \mathbf{R}(\hat{z}, \vartheta) \cdot \uparrow_{\hat{x}} \quad (47)$$

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 $\mathbf{R}(\hat{z}, 2\pi)$ must be a scalar, and in conjunction with Eq. 46 that the phase factors on the left-hand side of Eq. 47 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.

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 (little) Hamiltonian.

In the RQF, 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 QT, by contrast, quanton spin is monolithic and described entirely by two numbers: spin magnitude (s) and projection (s_z) onto any one geometric axis.

Spin Coupling to Rotational Momentum

Spin itself is a purely phasal property of W-state. Its linkage to rotational momentum, which is necessary to account for the phenomenology of spin-orbit coupling and magnetic moments, requires an additional physical axiom.

For some types of quantons, the axial alignment of spin to momentum is nominally in the same direction, whereas for other types, the alignment is opposite. Whether the alignment is same- or opposite-direction is a matter of convention; directionality of spin, which is phasal, is an arbitrary designation, whereas the directionality of momentum, which is palpably physical, is not.

In the RQF, spin is distributed as many little vortex arrows strapped onto the threads. The arrows can flex and thus vary spatially. P-state coordination, however, ensures that they collectively exhibit particle-like unity, such that the illusion of monolithic spin, consistent with all empirical evidence, is upheld.

2.4.3.2 Identical Particle Interchange

The theoretical minimum (Sec. 2.2.5.1) made the simplistic assumption that quantons are distinguishable, but we are now ready for a full reckoning with *identical particle interchange* (IPI).

Multi-Quanton W-state

The multi-quanton W-state locally consists of a list of single-quanton states: $\tilde{\psi}_1, \tilde{\psi}_2, \tilde{\psi}_3$, etc. These can be sorted in descending order: $\tilde{\psi}_1$ represents 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, but only finitely many quantons, with some manner of roll-off, have appreciably non-zero presence at any point.

Multi-quanton W-state, which in this context means quantons all of a single type, is a superposition of *pure* states of the form:

$$1 \otimes 2 \otimes 3 \otimes \dots \quad (48)$$

in which individual instances of the quantons are considered distinct and labeled. In the notation of Eq. 48, quanton instance 1 instantiates $\tilde{\psi}_1$, instance 2 instantiates $\tilde{\psi}_2$, and so forth. ' \otimes ' denotes collocation of quantons of the same type.

Tight Superpositions

Eq. 48 denotes a *pure state*. It differs fundamentally from the set-theoretic union in Eq. 16 in that order now matters.

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 that exist in Nature.

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

$$1 \otimes 2 \otimes 3 + 2 \otimes 3 \otimes 1 + 3 \otimes 1 \otimes 2 + 3 \otimes 2 \otimes 1 + 2 \otimes 1 \otimes 3 + 1 \otimes 3 \otimes 2 \quad (49)$$

In Eq. 49, 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. 49, except that odd-order permutation terms are negated. For $N = 3$:

$$1 \otimes 2 \otimes 3 + 2 \otimes 3 \otimes 1 + 3 \otimes 1 \otimes 2 - 3 \otimes 2 \otimes 1 - 2 \otimes 1 \otimes 3 - 1 \otimes 3 \otimes 2 \quad (50)$$

Track Structure of Fermionic W-state

IPI, like spin, introduces a new form of ontic structure in local W-state. For each distinct quanton type, the W-state consists of two “tracks”. When the W-state is rotated, the tracks transpose with one another, like a Möbius strip. Each track holds the negation of the state in the other track, enabling equal and opposites to coexist without canceling. Each track contains two groupings of terms, one consisting of even-order permutations of a designated reference pure state and the other consisting of odd-order permutations.

For fermions, the tracks undergo an odd number of half-twists per revolution (*i.e.*, rotation through angle 2π), whereas for bosons, the tracks undergo an even number of half-twists.

Spin-Statistics Theorem

We now consider the combinations of interchange symmetry and spin. To illustrate, a shorthand notation is adopted. Fermionic combinations are denoted in shorthand as: $(+-)(-+)$. The first parenthetic enclosure represents track A, the second track B. The ‘+’ on the left in track A denotes even-order permutations of the reference state. The ‘-’ on the right in track A denotes odd-order permutations. The $(+-)$ for track B indicates full negation of track A.

With half-integer spin, all four signs in the shorthands change after rotation through 2π along the Möbius strip, but we then have to swap the tracks and negate all the signs. That way, the original state is restored.

It follows that two combinations are tenable: fermionic combinations of half-integer spins and bosonic combinations of whole-integer spins. This finding concurs with empirical fact that bosons have integer spin and conform to tight superpositions of the form in Eq. 49, and that fermions have half-integer spin and conform to Eq. 50.

The Pauli spin-statistics theorem is vindicated, but the RQF analysis shows that it was reliant on assumptions (*e.g.*, positive energy solutions) that exceeded the simplicity of the W-state ontic structure.

Pauli Exclusion Principle

The Pauli Exclusion Principle (PEP) takes effect locally. If any two short fermionic threads, of the same quanton type cloth, with the same W-state try to collocate, they will force the entire W-state *for that quanton type* locally to zero.

2.4.4 Quantum Field Theory

2.4.4.1 Wave-Stuff

The RQF aspires to be a wholesale replacement of quantum field theory (QFT). From the outset, it has been designed and constructed as a fully relativistic theory whose principal ontic entity is W-state, which is primarily wave-like. W-state is physicality and local physics. It is composed of wave-stuff, which is distinctly quantum and non-classical in specific respects that have been spelled out.

2.4.4.2 Particle Likeness

QFT regards particles as field excitations. The RQF takes a somewhat different view. It is the wave-stuff that becomes excited, and particle-like holism is an emergent manifestation of P-state constraint that has effect on W-state to give the impressions of cohesion and lumpiness. QFT holds that fields are quantized via operators acting on states to ensure that energy and momentum appear in discrete packets (quanta). The RQF maintains that that is the physical result of P-state coordination, whose mandate ensures that energy-momentum manifest in W-state remains bundled as discrete quantons.

The term *quanton*, in the context of QFT, has two meanings: (i) varieties and flavors of wave-stuff, and (ii) aggregations of wave-stuff, whose cohesive lumpiness is not intrinsic to the wave-stuff itself but arises from P-state constraint. Fields, in the sense of QFT, signify wave-stuff aggregations composed of common quanton varieties.

2.4.4.3 Virtual Particles

QFT regards virtual particles as excitations of fields, often depicted as higher-order graph topologies in Feynman diagrams. They often lead to infinite results (ultraviolet divergences), which becomes a matter of fire-fighting (*i.e.*, mathematical cancellation via renormalization). The process is viewed as mathematically necessary, but physically arbitrary and not rooted in ontological principle.

The RQF regards “virtual particles” as pockets of intense unrest in the W-state, wherein order (coherence) is unable to take root. Islands of order can be thought of as akin to crystals growing in a eutectic solution. Virtual particles, in that view, are the sludge filling the remaining volume of the ingot.

2.4.4.4 Divergences and Renormalization

The P-state is the physical non-local renormalization mechanism, which stands to simplify calculations greatly. Ultraviolet divergences arise in QFT because QFT imposes no lower bounds on the microscopic scales at which excitations can occur. The lack of lower bound is dramatized in Feynman diagrams, depictions of which often convey self-similarity. In the RQF, the necessary lower bound is supplied by the compressibility limitation in the W-state, which cannot be compressed below the Compton wavelength - at least not without provoking violent revolt.

2.4.4.5 Non-Relativistic QM and QFT

What is the essential difference between non-relativistic QM and QFT? Why is it that the latter is held to be so much more advanced subject matter than the former?

The difference has to do with the restlessness of self-energy in W-state. The lesson of zbw has taught us that restlessness is an indelible fact of life in the quantum realm. However, some simplifications are justified in the low-energy regime of W-state phenomenology. One is that in low-energy settings of stability (*e.g.*, involving only electrons and ordinary non-radioactive nuclear matter), the number of quantons is, for all practical purposes, reliably constant. Quantons then look, as far as we can tell, as if they were particles with true identity of their own (IPI notwithstanding). The analytic treatment of the W-state can then be simplified greatly.

Quanton Transformation

QFT is primarily geared for high-energy physics, wherein quanton types and counts are subject to dynamic change. Two examples are: (i) pair production, wherein electron-positron pairs are created in collisions whose energy threshold exceeds $2mc^2$, and (ii) muon decay, *viz.*,

$$\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu \tag{51}$$

In high-energy scenarios such as these, the P-state mandate becomes qualitatively different from that prevailing in the low-energy realm. It softens, such that the numbers and flavors of quantons in play becomes fluid and negotiable. QFT encapsulates the transformations as vertices in Feynman diagrams, but rules out any deeper insight or visualization. The RQF, on the other hand, is able to reveal detail of how the W- and P-state dynamics play out within the vertices.

Non-relativistic QM

Non-relativistic QM, as it is conventionally called, signifies the low-energy regime in which quanton types and counts are reliably fixed. However, “non-relativistic” becomes a misnomer, for two reasons: (i) zbw cannot be ignored, and (ii) Lorentz-covariant dynamic law is still needed to describe how observers moving at high velocities relative to low-energy systems would describe them.

2.5 Unification of Quantum Theory with Classical Electromagnetism

2.5.1 The Unification that Never Happened

2.5.1.1 What are Photons?

The First Discoveries

In 1905, a young patent clerk came upon the astonishing insight that the empirical phenomenology of the photoelectric effect could be explained with the supposition that the incident light beam is composed of quantal lumps. The lumps have energy $E = \hbar\omega$, where \hbar is precisely the new fundamental constant that Planck in 1900 discovered is needed to yield the formulaic result for the thermal radiation spectrum, which derives from modal discreteness in the blackbody cavity. The quantum revolution was set into motion, and many great things came because of it. But we stand now 120 years later, with basic questions unanswered.

Broken Relationships with Classical Theory

Neither Planck nor Einstein, nor any of the founders, was ever able to answer the very basic question: What *are* photons? To do so would have required explaining how the lumps intermesh seamlessly with Maxwell's classical field theory. But Einstein was unable to do that - not at all because he was in any way a lazy dog, but because of the conceptually intractable nature of the quantum realm that he and Planck had stumbled upon. The conceptual intractability is for real and still with us in the 21st century. The conventional QT that grew from their discoveries is symptomatic of that in many respects, two of which are particularly important concerning photons: (i) Designed as an instrumentalist framework, it is unable to answer basic story-telling questions, such as *what* photons are. (ii) It is broken in its relationships to classical mechanics and classical electromagnetism. The two classical theories were orphaned and deprived of participation in the quantum revolution. Essentially the same is true, of course, of GR, which is why QG has been out of reach for so long.

Electrostatic and Radiative Fields

It is the job of the RQF to answer the very basic question that Planck and Einstein could not answer. What is the ontic relationship between photons and the field-stuff of the Maxwell-Faraday theory? At the outset, some facets of the challenge can readily be foreseen. First, photons, by themselves, cannot represent a wholesale replacement ("quantization") of classical electromagnetic field theory, for the simple reason that not all field-stuff is radiative. Classical electromagnetic theory accounts for electrostatic fields, radiation (*e.g.*, from radio antennas), and a panoply in between. Those diverse forms are all united under a single theoretical roof. They consist seamlessly of a single kind of field-stuff and are governed by a concise set of dynamics equations. Realist QT must reinstate that full gamut and intermesh it seamlessly with QT.

2.5.1.2 The Missing Chapter

The Overlooked Unification

QT is no less in need of unification with classical electromagnetism than with gravity, but it was a unification that never happened. It is a missing chapter in the history of science that should have been written, but never was.

What is worse is that there was no perceived need for unification, unlike with gravity. The eventual result was quantum electrodynamics (QED), which was a winning horse, but it also exacerbated deep foundational issues. It was a fount of calculations that achieved fantastically precise agreement with experiment, but it was ultimately not the answer to the true unification that was needed. It falls on the RQF to produce that unification.

Template for Quantum Gravity

When we face QG in Sec. 3, we will rely heavily on insight on what makes gravitation essentially different from electromagnetism. We will see that the quantum nature of electromagnetism, for reasons closely related

to its specific nature, is strongly multi-situational, whereas gravitation, being quite different, gives way to uni-situationality. The unification of QT with classical electromagnetism is crucially needed to support that insight, but once it is available, the quantum gravity unification becomes astonishingly simple.

2.5.2 Unification Solution

The RQF adopted classical mechanics and reinstated it as part and parcel of QT. It will now do the same for electromagnetism.

2.5.2.1 Classical Situations

Consider one QWE of one quanton in a multi-quanton W-state and another QWE - of the same or a different of quanton - at the same or a different point. Are they part of the same classical situation? The answer is yes if and only if they both contribute, as sources, to the same electromagnetic field (regarded itself as a classical situation). That is, the source contributions of the two QWE's *sum vectorially*, just as in classical electromagnetic theory.

Up to this point, W-state structure (*e.g.*, QWE superpositions, fermionic track structure) has preserved separate situations and precluded cancelation of equals and opposites, but it is different now when it comes to electromagnetic fields, which have to be sourced from multiple locations and combine the contributions through vectorial summation. The introduction of classical electromagnetic fields compels us to accommodate the concept of *extended multi-situationality*. That is, multiple short threads, distributed in space-time, together with the electromagnetic fields that they produce, must all belong to a common *classical situation*.

Membership in the same classical situation defines an equivalence class partitioning, \mathcal{E} , of QWE's in the W-state. Different field situations can coexist and interpenetrate one another as different classical situations, just like different QWE's (belonging to different equivalence classes) within the W-state of charged matter.

The upshot is that the W-state structure of charged matter is distinctive in that it has a partitioned structure, wherein each element of the partition represents a distinct classical situation. Charged matter and electromagnetic fields are distinctly multi-situational.

2.5.2.2 Elimination of Infinities

The intermeshing of classical electromagnetism with the quantum theory of matter has been achieved, just like with classical mechanics. W-state now features superpositions of matter and electromagnetic fields belonging to different classical situations. Within each situation, the sources and fields retain their smooth continuity and finiteness, just as in classical theory. Because QWE sources are spatio-temporally distributed and infinitesimal elements, infinities are eliminated, and renormalization is obviated.

2.5.2.3 Differences with Gravity

Consider a short thread of electromagnetic field W-state (*i.e.*, in a single situation) at a certain point, \underline{x}_f , and the short matter threads belonging to that same situation at source point, \underline{x}_s , causally preceding \underline{x}_f . Every quanton present (to varying degrees) at \underline{x}_s contributes exactly one short thread to the situation.

The same, in principle, holds for gravitation, but the consequences are dramatically different, because of essential differences in the two forces. Consider the combinatoric space whose elements consist of a short thread being taken from each quanton. Each such thread contributes to the field tensor (or, equivalently, vector potential) at \underline{x}_f based on the quanton charge, the thread velocity, and the magnetic moment affixed to its spin. The combinations are diverse, especially for the magnetic contributions, which are sensitive to the velocities. Different elements in the combinatoric space (*i.e.*, different classical situations) can produce very different tensor values at \underline{x}_f ; hence the potential for multi-situationality.

The gravitational multi-situationality is much less at the outset for two reasons: (*i*) Gravitational attraction is unsigned. (*ii*) Electric and magnetic components of the tensor, generally speaking, are co-important and go hand-in-hand, whereas velocity-dependent gravitational phenomenology is obscure and exotic (*e.g.*, Lense-Thirring) and not apparent in everyday Newtonian gravity. The lack of *a priori* situational diversity greatly lessens the deconfliction burden on gravitational decoherence, helping make it extremely fast.

2.5.2.4 Radiation in Lumps

Aside from multi-situationality, the major difference between the new electromagnetism, integrated into QT, and the old classical theory is will be that it will (must) permit radiation only in lumps. It follows that sharp distinction between radiation (photonic lumps) and electrostatic fields is an emergent dichotomy.

An incipient photon can be thought of as a bulge in the electrostatic fields in the vicinity of the source. The term *electrostatic*, in this context, is being stretched to signify electromagnetic fields tightly bound to their sources. If the sources move and shake, so too do the electrostatic fields. A nascent photon, once ripe (having accumulated $E = \hbar\omega$), “buds off” from the electrostatic field. Radiant fields, unlike electrostatic fields, detach from the sources and take on a life of their own. The two categories (electrostatic and radiant) are seamlessly one and the same field-stuff, but are otherwise sharply different dichotomously in this respect. This is the answer to the question of what photons really *are*.

2.5.2.5 Story-Telling Glimpse into Feynman’s Vertices

The “budding off” that occurs when a photon is created can be visualized as a drop popping up out of a pond. Photon absorption is the opposite process, like a drop plunging into the pond. The photonic W-state can then be thought of as “melting away” into the electrostatic fields of the absorber material. This is the realist tale of what transpires in the vertices of Feynman diagrams.

2.5.3 Aharonov-Bohm Effect

2.5.3.1 Classical Puzzlement

The Aharonov-Bohm (AB) Effect is a third facet of the new electromagnetism, beyond the reach of the old classical theory to explain. In the two-slit experiment, a solenoid is placed midway between the slits. As electrons are shot through the apparatus, their W-state divides and works its way through the slits, steering clear of the coil. When the two halves of the W-state recombine, it is found that the interference pattern on the screen shifts, by an amount dependent on the solenoid current. This is a puzzling phenomenon because it cannot be explained by classical electromagnetic theory. Because the electromagnetic fields (\mathbf{E} and \mathbf{B}) outside the solenoid are zero, the presence of the solenoid, by classical expectation, should have no effect on the electron motion through the apparatus or the interference pattern.

Standard QT readily explains the phenomenon by showing that the shift is proportional to the vector potential, $\underline{A} = (\mathbf{A}, \phi/c)$, integrated over a closed loop circumscribing the solenoid. As an instrumentalist explanation, this clearly works and is correct, but it offers no insight into how the W-state is able to sample the information content of the line integral, considering that the \underline{A} field itself, by classical reckoning, has no local meaning of its own.

2.5.3.2 Preferred Gauge for Long Thread Dynamics

The dynamics in the two-slit experiment are purely unitary, and so the RQF must be able to explain the phenomenon within the scope of Rule 1 W-state dynamics. Conjecture that it might be a non-local effect, such as P-state coordination during the short interval that the rest manifold cuts through the solenoid itself, is wrong.

The phase rates of the long threads are determined directly by the local action rate, which is given by the Lagrangian (Eq. 36). That the Lagrangian, in realist QT, is absolute and directly dependent on \underline{A} implies a preferred gauge that drives the long thread dynamics.

2.5.3.3 Gauge Invariance in All Interference Effects

In the RQF, the preferred gauge is needed in the theory to drive the phase rates of the threads. As an empirical matter, thread phases matter only insofar as they can produce interference effects. However, interference effects depend only on phase differences occurred along different paths, which converge through lensing. Those phase differences are closed-loop integrations and are therefore gauge-invariant.

2.5.4 Thermal Radiation Spectrum

2.5.4.1 Festschrift Essay

At the 125 year mark of his great seminal discovery that got the whole show rolling, this subsection is an essay dedicated in honor of Max Planck. The RQF revisits the blackbody cavity and the thermal radiation spectrum.

2.5.4.2 Modal Discreteness

The Crucial Piece of Phenomenology

The gateway to Planck's seminal discovery of energy quantization was *modal discreteness* in the cavity. It is the one and only phenomenon that ultimately matters, caught Planck's attention, and gave birth to the quantum revolution. But it is puzzling in a number of respects, not the least of which is that it implies a highly ordered state of affairs, both globally (*e.g.*, mode shapes and frequencies fitted to the cavity size and shape) and locally (*i.e.*, in boundary conditions that must be satisfied at all points on the cavity walls). Yet the local situation of any electron at the cavity surface is the utter opposite of order. It is highly agitated thermally - buffeted non-stop intensely by micro-measurement activity. How does that fitful local activity, at atomic scale, in aggregate produce infrared photons, whose wavelengths are many orders of magnitude greater? These circumstances strongly suggest coordinated movement of electrons at different points far apart on the cavity surface.

Modes and Boundary Conditions

In the customary textbook treatment, the cavity interior is modeled as a resonator, a mathematically tractable problem of classical electromagnetism. The resonator model provides the conceptual explanation for modal discreteness. The textbook, however, gives the student the impression that the standing wave solutions represent literal truth. The proper interpretation is that they signify the maximum extent that islands of order in the cavity interior can reach, both spatially (filling the volume) and in longevity. In the hydrogen atom, the maximal islands are the Laguerre polynomial solutions of the Schrödinger equation. Traditional QT pockets and trumpets these results, and exhorts us to trust the formalism.

The textbook also implies that the boundary conditions at the cavity walls - those of a perfect conducting surface (*i.e.*, \mathbf{E} normal, \mathbf{B} tangential to the walls) - are literal truth. That is a mathematical expediency, adopted only to make the analysis tractable and formulaically simple (for a rectangular cavity). Physically, however, a perfect conductor reflects, rather than absorbs, incident radiation - a contradiction quietly ignored.

The actual boundary conditions for the absorbent cavity wall are similar *in kind* to those of the perfect conductor but different in detail. It is non-trivial and important mathematical fact that the difference in detail does not matter, when it comes to the top-level order that ultimately emerges from the chaos. Notably, the modal density at high frequency is independent of the exact boundary conditions.

Absorptivity and Emissivity

The textbook in passing cites Kirchoff's formula ($a = e$), which looks for all the world like a tautology, but it does not offer first-principles operational definitions of absorptivity and emissivity for blackbody surfaces. The RQF is well-positioned to do that.

Absorptivity is the simpler of the two. A beam impinges upon a surface. Absorptivity is the proportion that gets absorbed (convected into the interior of the material); the rest is reflected.

Emissivity pertains to radiant energy that convects from the inside to the surface. The emissivity is the proportion that makes its way out; the rest is internally reflected.

Order from Chaos

The blackbody cavity is a special and rarefied kind of order. It is a highly repeatable and quantitatively precise kind of order that is independent of cavity shape (assumed to be macroscopic) and the detailed nature of the boundary conditions. It is furthermore a quantitative order of a universal character, involving only the fundamental constants \hbar and c , and the temperature. The mathematical result is a truly beautiful formula for the thermal

radiation spectrum, from which the supporting empirical laws of Stefan-Boltzmann and Wien are easily derived and validated.

2.5.4.3 Planck's Oscillators

Planck used the vague term “oscillator”, which in his day signaled ignorance about the microscopic motions in the cavity, if not also a noncommittal position on the question of atoms. Realist theory, 125 years later, enables us to appreciate that that term fortuitously remains relevant and useful. It can be ascribed to long-range correlations in the fitful local motions of the electrons, orchestrated by the P-state. Hence, there is more to oscillators than just single atoms.

P-state Coordination

P-state coordination plays a role in coordinating the oscillator motions, but only up to a point. The P-state, loosely speaking, “knows” that the electrons have to radiate excess energy, and that almost all of it must be at long wavelengths. It can coordinate micro-measurement outcomes and thereby indirectly influence the W-state evolution in ways that favor incipitation - and sometimes sustained snowballing - of nascent photons.

Why “up to a point”? Does the P-state solve Maxwell's equations for the entire cavity and direct synthesis of standing wave photonic solutions? No; that is too far-fetched. The P-state is only permitted to implement its mandate via a hypercubic PDF. The P-state sows the seeds that favor incipitation of photonic lumps, which then have to work through some trial and error to get the mode shapes and frequencies right. And even that may be too much to expect; it may be that cavity photons are short-lived, bouncing back and forth a few times and dying because they cannot get the global boundary conditions quite right. Modes, insofar as they almost get the shape and boundary conditions right, are islands of order in a sea of chaos.

2.5.4.4 Quantum Statistical Mechanics

The cavity is replete with chaotic dynamics, among the surface currents at the walls and the photonic fields in the interior. Realist QT now gives us a powerful means of investigating the deep specific nature of this layer.

Viewed over time, the electrons at the walls and the fields in the interior jointly constitute an ergodic ensemble. The modal discreteness emerges as a stationary steady-state feature of the ensemble. Reductionist analysis of the physics partitions the microscopic state into two major parts: (*i*) the sea of electrons at the cavity walls, which are modeled as a 2D charge-current density and fermionic gas, and (*ii*) the sea of photons in the interior, which is a superposition of ephemeral field threads and a bosonic gas.

Quantitative analysis of the microscopic chaos - and the order that ultimately emerges - is the subject of quantum statistical mechanics (QSM). Its programmatic aim, in concept, is to construct a stochastic generator model of the W-state, followed by statistical analysis of the ensemble results.

Instrumental Probing

Realist QT, in application to W-state, permits us to speak of thermal radiation inside a fully closed cavity, as an objectively real situation, without observers (like the tree in the forest). That is a baseline scenario that simplifies the mathematical analysis. Alongside the baseline, we have a modified scenario, in which the experimenter drills a little hole down through the cavity wall and peers in with an optical pyrometer. Quantitative comparison of the scenarios shows that the hole, if small enough, does not perturb from the baseline significantly. It thus amounts essentially to an unintrusive passive observation activity on quantum phenomenology.

2.6 RQF Integration with the Nuclear Forces

The ground that has been covered thus far is, roughly speaking, the province of atomic and molecular physics. It is principally concerned with electromagnetism and the ontology and dynamics of quantum physics that is, for the most part, well-described by the low-energy regime of QFT.

The province, which can be thought of as the upper half of the microscopic realm, is largely conterminous with what has traditionally been the core curriculum of quantum pedagogy, which is anchored at atomic-scale

phenomenology. From there, the curriculum can proceed up or down, and the RQF Trilogy is no exception. Sec. 2.6 covers the downward descent into the realms of the weak and strong nuclear forces, which constitute the lower half of the microscopic realm.

The upward ascent conventionally encompasses the province of condensed matter physics. That, however, that is implicitly covered in Sec. 2 as an extension of low-energy QFT (traditionally equated with non-relativistic QM). Upward ascent in Sec. 3 deals with GR.

2.6.1 Standard Model Symmetries

We proceed to examine fundamental symmetries in W-state ontology. The symmetry operations and their group-theoretic structure relate directly to the quanton types in the Standard Model (SM).

2.6.1.1 Symmetry Operations

We consider four operations within each family. They operate on three attributes of the W-state:

- rotational momentum (L_z)
- spin (s)
- phase rate (ω)

The four operations are:

Table 1: Symmetry Operations of the Standard Model

Parity inversion	$(L_z, s, \omega) \rightarrow (-L_z, s, \omega)$
Time reversal	$(L_z, s, \omega) \rightarrow (-L_z, s, -\omega)$
Charge conjugation	$(L_z, s, \omega) \rightarrow (L_z, s, -\omega)$
Turn particle upside-down	$(L_z, s, \omega) \rightarrow (-L_z, -s, \omega)$

It is noted that:

- L_z is mechanical momentum, whereas spin is phasal only.
- L_z inverts under time reversal (T), whereas spin does not.
- Parity (P) is a spatial operation and affects only L_z .
- Charge conjugation affects only phase rate.
- CPT (three operations in succession) holds exactly.

2.6.1.2 Quanton Enumerations

A total of eight (8) cases, enumerated in Table 2, arise with each family.

As many as four distinct quanton types can occur with a family, turning upside-down does not produce a different type.

- For charged fermions (quarks and leptons), P-inversion symmetry *usually* holds. When it does hold, it follows that $\bar{q} = -q$, and so there are effectively only two quanton types in the family.
- For neutrinos, $\omega = 0$ (*i.e.*, the W-state does not pulsate), from which charge neutrality follows ($q = -q$). However, q and \bar{q} are distinct. The non-pulsation of neutrino W-state is closely related to the (near) masslessness. Neutrinos, as far as the evidence indicates, are unique as non-pulsating fermions. As such, they participate only in weak interactions.

Table 2: Quanton Enumerations

$(+L_z, +s, +\omega)$	q	reference particle
$(+L_z, +s, -\omega)$	$-q$	charge conjugate of q
$(+L_z, -s, +\omega)$	$-\bar{q}$	charge conjugate of \bar{q}
$(+L_z, -s, -\omega)$	\bar{q}	anti-matter counterpart of q
$(-L_z, +s, +\omega)$	$-\bar{q}$	charge conjugate of \bar{q}
$(-L_z, +s, -\omega)$	\bar{q}	anti-matter counterpart of q
$(-L_z, -s, +\omega)$	q	reference particle
$(-L_z, -s, -\omega)$	$-q$	charge conjugate of q

- Quarks and leptons, by contrast, are fermions with non-zero phase rate. This distinctive property *fundamentally defines* electric charge. Given any two charged quantons (of the same or different families), whether they repel or attract hinges on whether their phase rates are like or opposite (respectively).

2.6.1.3 Track Pairing

In the RQF, the W-state of any fermion or boson consists of a Möbius strip, with tracks A and B, and then the next lower level of W-state, henceforth referred to as *core dynamic state*, internal to each track. The core dynamic states are always exactly equal and opposite in the two tracks, for fermions and bosons alike. As a visualizable analogy, the strip can be regarded as a pair of conjoined toothpaste tubes. The core dynamic states are the toothpaste contents of the tubes.

The two tracks are perfectly anti-symmetric. Neither has any preferred status over the other. Anything that can be said about the internal state in either track, in isolation, can be said about the other. The relational ontology only countenances discourse that respects the anti-symmetry.

Consider now interaction between two quantons (of the same or different kinds), wherein the two are juxtaposed. What does the relational ontology allow to be said? The answer is in a new physical axiom, which holds that Nature has a way of *associating* track A of one with that of the other, and similarly for B. That is, Nature deems one particular track in the first quanton and a track in the second to be the A-and-A pairing and for the remaining two tracks to be B-and-B. The designations “A-and-A” and “B-and-B” are interchangeable and anti-symmetric.

Charged quantons repel (attract) if the phase rates within the A-and-A pairing are of same (opposite) sign.

2.6.1.4 Helicity and the Annihilation Condition

If the two quantons of a matter and anti-matter pair, conditions for mutual annihilation are ripe if and only if the core dynamic states are equal and opposite within the A-and-A pairing (and, of course, also for the B-and-B pairing).

Consider a scenario in which matter (q) and anti-matter (\bar{q}) come into contact⁸. Suppose that q has dynamic attributes (p_z, L_z, s, ω) , where p_z is the translational momentum. We propose the following operations to obtain \bar{q} , which, in the center of mass frame, must have opposite momentum $-p_z$:

- Copy q .
- Transform q to \bar{q} , yielding $(p_z, -L_z, s, -\omega)$.
- Turn \bar{q} upside-down, preserving the directional relationship $(\underline{p} \cdot \underline{L})$ between the translational and rotational momentum, yielding $(-p_z, L_z, -s, -\omega)$.

It is noted that the conditions for annihilation are almost right, except that L_z is same-signed for the two.

The P-state mandate calls for unease to be minimized by doing away with rest mass altogether, which can be achieved only if all dynamic attributes cancel in the A-and-A pairing. Preserving the directional relationship

⁸In this context, q may denote neutrinos or charged leptons.

between \underline{p} and \underline{L} , as is assumed in the preceding naive definition of “turning upside-down” does not accomplish that. Instead, the P-state must coax them to have opposite directions for q and \bar{q} . This provides physical insight into and deep explanation of what is conventionally recognized as the oppositeness of *helicity* in q and \bar{q} .

The annihilation condition for q and $-q$ is also realized, but exactly according to the above recipe. This explains why \bar{q} and $-q$ are for all practical purposes one and the same: the P-state enforces the helicity constraint, without which they would be different quantons.

2.6.1.5 Parity Violation

Empirical evidence, such as the beta decay phenomenology discovered and investigated by Wu, clearly establishes that P-inversion symmetry is *not* inviolate. Parity violation is an indication that the P-state is not always unfailingly effective in enforcing helicity, or equivalently, indistinguishability of \bar{q} and $-q$. In the regime of violation, q , $-q$, \bar{q} , and $-\bar{q}$ are technically all distinct.

2.6.2 Electro-Weak Processes and Structure

This section comprehensively addresses the structure of the electro-weak sector of the Standard Model, as it exists independently of P-violation phenomenology.

2.6.2.1 Track Pairings in Muon Decay

We now turn attention to muon decay, which, without loss of generality, is represented by the following two-step process:

$$\mu^- \rightarrow W^- + \bar{\nu}_\mu \quad (52a)$$

$$W^- \rightarrow e^- + \bar{\nu}_e \quad (52b)$$

Consider the last step (Eq. 52b) in the process first. The track pairing consists of core dynamic state in track A of the electron and associated with that in track A of the anti-neutrino ($\bar{\nu}_e$). The track A state in the W^- , prior to the last step, is a blending of the two. Analogous to a chemical compound, it is a distinctive type of wave-stuff specific to the W^- . During the decay process in Eq. 52b, a QFT-like metamorphosis takes place, wherein the compound is transformed into the final W-state products. The interior of this Feynman diagram vertex is like a chemical reaction, wherein the P-state mandate effects a transition from a quanton count of one to a count of two.

The electron and anti-neutrino ($\bar{\nu}_e$) are fermions in the lowest-energy tier 1 of the Standard Model. As such, their track structure, which is henceforth referred to as *torsional state*, characteristically has just one half-twist per revolution - the smallest possible number for fermions. The W^- has two half-twists, which signifies a more contorted geometry, which is uneasy and susceptible to decay.

Consider now the first step in the process (Eq. 51a). The track pairing consists of the compound state in track A of the W^- and core dynamic state in track A of the muon anti-neutrino ($\bar{\nu}_\mu$). The track A state in the muon, prior to the first step, is a blending of the two, just as in the second step.

The muon is a fermion in tier 2. As such, its torsional state characteristically has three half-twists per revolution.

2.6.2.2 The Electro-Weak Ladder

A pattern is becoming apparent: Number of half-twists in the Möbius strip per revolution is the signature geometric feature of torsional state (itself a facet of W-state) that indicates tier level in the Standard Model. Contortion of this kind is energetically costly and provokes revolt except in the minimum-energy configuration (tier 1). It suggests, however, that higher-order tiers are mathematically compatible with geometric architecture of W-state, and that the number of known tiers (three) is a soft provisional number, rather than a hard number written in mathematical stone. That does not at all mean, however, that there is any practical possibility of detecting a fourth tier in accelerator experiment.

Muon decay, as an archetypal electro-weak process, represents the lowest rung in a ladder through which higher tiers can, in principle, be reached via a sequence of generalized decay processes of the form:

$$\lambda_{t+1} \rightarrow W_t + \bar{\nu}_{t+1} \quad (53a)$$

$$W_t \rightarrow \lambda_t + \bar{\nu}_t \quad (53b)$$

in which t denotes tier number and λ_t denotes the lepton in tier t (*i.e.*, electron or positron for $t = 1$, muon for $t = 2$, etc.). It is emphasized that Eqs. 53 represents observed proven phenomenology only for $t = 1$, which coincides with the muon decay in Eqs. 51. $t > 1$ represents hypothetical, but logically straightforward and conservative, generalization of the Standard Model to which the RQF points. Notably, it predicts the existence of boson W_2 (different from the known $W_1 = W^-$) resulting from decay of λ_3 (tauon).

Torsional state is the W-state feature that distinguishes the tiers. The number of half-twists per revolution is odd $(2t - 1)$ for λ_t and ν_t and even $(2t)$ for W_t .

2.6.2.3 Neutral Current Decay Modes

The ladder in Eqs. 53 and its anti-matter twin account for the decay of higher-tier leptons and W-bosons. It is a single determinate sequence of steps ending with an electron (or positron in the twin).

Neutral current decay, wherein a Z^0 boson decays into an electron-positron pair, is a zip combination of the ladder and anti-ladder. It too is envisioned to generalize as a tiered sequence, *viz.*,

$$Z_t \rightarrow \lambda_t + \bar{\lambda}_t \quad (54)$$

followed by the single-sequence decay modes for the leptons (if $t > 1$).

As a matter and anti-matter duo, the core dynamic states of the electron and positron are opposites. Under annihilation conditions, track A of the electron is the inverse of track A of the positron, and similarly for B. This suggests that the internal state of track A in Z_t is itself a dual-track structure, in which equal and opposite core dynamic states coexist.

The combination of the single-sequence electro-weak ladder (Eqs. 53) and anti-ladder, and the ladder zip (Eq. 54), is a conservative generalization and expansion of the Standard Model. As with the W-bosons, only $Z_1 = Z^0$ is observed proven phenomenology. Z_t , like W_t , has $2t$ half-twists per revolution in its torsional state.

The core dynamic state of Z_t bosons is itself a nested structure, consisting of coexisting equal and opposite phase rates (resulting in net zero electrical charge). The non-zero internal phase dynamism, however, ensures that the neutral bosons remain subject to the de Broglie relation (Eq. 7) linking kinematic and phasal state attributes.

2.6.2.4 Scalar Mass of the Neutrino

The non-pulsation ($\omega = 0$) that distinguishes the neutrino is incompatible with the de Broglie relation (Eqs. 7), necessitating an important ontological distinction. If the de Broglie relation did apply, as it does for charged quantons, the neutrino would have to be strictly massless (*i.e.*, $m = 0$ in Eq. 8), contradicting empirical evidence. A special physical axiom exempting the neutrino from the de Broglie relation is therefore stipulated: Its empirically measurable non-zero mass is introduced in as a scalar appendage to the W-state dynamics.

Neutrinos, like photons, have translational momentum. However, they are exempt from the de Broglie relation, from which it follows that they do not exhibit the spatio-temporal phasal variation (*i.e.*, $\omega \neq 0$) characteristic of QWE's.

2.6.2.5 Achromatic W-state

In summary, the overall W-state structure of leptons, neutrinos, and the electro-weak bosons, henceforth referred to as *achromatic* W-state, consists of:

- **Core dynamic state:** This consists of kinematic (translational and rotational momentum) and phasal state. Spin (phasal) and rotational momentum are distinct but always go hand-in-hand. For leptons and bosons, translational momentum, $\underline{p} = (\underline{p}, E/c)$, is directly related to phasal state, $\underline{k} = (\underline{k}, \omega/c)$, through the de Broglie relation for leptons and bosons, but not neutrinos.

- **Torsional state:** This defines the Möbius strip topology, and applies to all. Between decay events, it is a fixed discrete value.
- **Scalar mass:** This applies to neutrinos only. It is compartmentally separate from the core dynamic and torsional state components.

The distinction between core dynamic and torsional state is important: It enables higher-tier leptons, neutrinos, and weak bosons to have small spin quantum numbers despite larger contortion numbers. It is noted that neutrinos are distinguished across tiers only by torsional state and possibly also mass; core dynamic state is not an intrinsic differentiator.

The concept of torsional state offers fundamental insight into *why* tiers of the Standard Model exist in the first place. It has to do with contortion, which suggests a tense energetic form of unease that Nature abhors. Leptons (other than the electron and positron) and bosons can do something about it by decaying, whereas neutrinos apparently cannot. Hence, ν_μ and ν_τ have no further recourse for decay via the electro-weak ladder/anti-ladder prescribed by Eqs. 53-54.

The full inventory of electro-weak quanton types and their empirically observed (or predicted) stability states are accounted by the ladder/anti-ladder (Eqs. 53) and zip (Eq. 54). The quanton inventory and W-state structure are said to be *achromatic* in that they are purely electro-weak and do not involve quarks or gluons.

2.6.2.6 Neutrino Oscillation

That neutrinos have non-zero translational momentum-energy implies that they are still subject to the P-state mandate to enforce helicity. The RQF interpretation of neutrino oscillation holds that that variation *may* provide a torsional release outlet for the higher-order neutrinos. That suggests the possibility of direct decay of ν_μ to ν_e (and its anti-matter counterpart), with the scalar mass difference between $t = 2$ (muon tier) and $t = 1$ (electron ground tier) giving expression to the torsional energy release. If empirical evidence of neutrino oscillation turns up, it would justify proposal of a neutrino decay ladder separate from the decay mechanisms for the leptons and bosons in Eqs. 53-54.

2.6.3 Electro-Weak Parity Violation

2.6.3.1 Parity Violation Phenomenology

The development of achromatic W-state in the preceding section, which assumes perfect symmetry between the ladder and anti-ladder, would be the final word on electro-weak ontology and decay processes, were Nature strictly symmetric under parity (P) inversion. The RQF interprets the supposition of P-invariance to mean that the helicity constraint, favorable to mutual annihilation of q and \bar{q} is perfectly enforced at all times (even if matter and anti-matter are not in near contact), which is functionally equivalent to an exact symmetry in fundamental law (*i.e.*, that q and \bar{q} are, by definition, one and the same quanton type). Experimental evidence of P-violation, in the RQF view, is an indication that helicity is not perfectly enforced under all circumstances.

P-violation is established empirical fact. The phenomenon was conclusively demonstrated by Wu's experimental observation of preferential electron emission in the beta decay of cobalt (^{60}Co) nuclei, *viz.*,



Wu and team observed that the electrons were preferentially emitted in the direction opposite to the spin of the cobalt nucleus. They saw that more electrons emerged in one direction (opposite the nuclear spin) than the other. Were parity not violated, that would not happen. Nature thus evidently does *not* treat the emanation process and its geometric mirror image equally. Parity violation in the weak nuclear force (beta decay processes) is established empirical fact.

The RQF offers light into *why* helicity is not perfectly enforced. It is usually, but not always, the favored probabilistic outcome of P-state mediation⁹, which, figuratively speaking, seeks to make both the electromagnetic and nuclear forces (within the cobalt) happy. If the global optimization criterion could always be satisfied by

⁹Note the dual usage of 'P' in the present context.

optimizing both separately, P-violation would be far less common, if not altogether nonexistent. The competing grievances of the electromagnetic and nuclear forces of the P-state mediation within the cobalt amount to a form of “cross-talk” between the two.

2.6.3.2 Weak Isospin

The first facet of cross-talk phenomenology pertains to *weak isospin*, commonly known as T_3 . The Wu experiment revealed the following results:

Table 3: Weak Isospin Results

Doublet designation	Particle	T_3	RQF mechanical interpretation
L	ν_e	+1/2	L_z twisted up
L	e_L^-	-1/2	L_z twisted down
R	$\bar{\nu}_e$	0	L_z not affected (flat)
R	e_R^-	0	L_z not affected (flat)
R	e^+	0	L_z not affected (flat)

The results indicate splitting (analogous to the Zeeman effect) in the left (L) doublet sector consisting of the electron and neutrino (ν_e), but not the anti-matter counterparts in the right (R) sector. The RQF interprets the results as an asymmetry in the P-state mediation that imparts a mechanical effect to the left, but not the right, doublet.

The RQF accommodates the empirical finding by introducing a “secondary twist” into the core dynamic state of the achromatic W-state. The secondary twist applies a local rotation to the momentum component (L_z) and phasal spin (s), but not to the phase rate (ω) associated with electric charge. The modification enables the W-state to encode the two necessary phase relationships: one governing CP symmetry (primary twists) and the other governing W/Z coupling. This geometric explanation resolves and alleviates a major complexity of the Glashow-Salam-Weinberg (GSW) model of electro-weak cross-talk. It enables the RQF to explain the phenomenology in straightforward physical terms, without invoking abstract mathematical symmetry fields.

2.6.3.3 Weak Mixing Angle

The second key facet of cross-talk phenomenology that GSW investigated pertains to the electro-weak mixing angle¹⁰ ($\sin^2 \theta_W \approx 0.23$), which is an empirical value that quantifies how the momentum (L_z) and phase rate (ω) attributes of the W-state combine to form the neutral mediators (*i.e.*, Z^0 and gamma photons emanating from annihilations) under the P-state mandate and the global constraints that it imposes.

Geometrically, θ_W signifies a measure of structural impedance within the W-state. It essentially quantifies the energy cost of inducing a localized secondary twist in L_z compared to inducing a temporal phase rate change (ω). The value $\sin^2 \theta_W \approx 0.23$ quantifies the overall stance (preference) of the P-state vis-à-vis the two forms of competing W-state dynamism (*i.e.*, between the electromagnetic and nuclear forces), ensuring that the unified electro-weak dynamics are internally consistent across both the charged and neutral quanton sectors.

2.6.4 Chromodynamics

This section addresses the structure of the chromatic sector of the Standard Model, which is concerned specifically with quarks, gluons, and the strong nuclear force.

¹⁰The ‘W’ in θ_W is named for Weinberg.

2.6.4.1 The Chromatic Domain

The *chromatic domain* is an inner sanctum inhabited by quarks and gluons and in which the strong force reigns. It can be thought of as a privileged exclusive interior ecclesiastic domain, in contradistinction to the achromatic domain, which is an exterior secular domain.

Chromatic State

The wavefunctions of quarks and gluons are conventionally written as a product of four factors, *viz.*,

$$\psi = \psi_{\text{space}}\psi_{\text{spin}}\psi_{\text{flavor}}\psi_{\text{color}} \quad (56)$$

The RQF equates $\psi_{\text{space}}\psi_{\text{spin}}$ what has been called core dynamic state and ψ_{flavor} with torsional state. Both concepts apply equally in the chromatic and achromatic domains. ψ_{color} , on the other hand, is exclusive to the chromatic domain.

Chromatic state, in the RQF, is the quantum chromodynamic (QCD) concept of *color* couched in relational ontology. It is the physical origin of the three-ness of the color palette (R, G, B) and baryons. Holding any two quarks in juxtaposition, the relational ontology permits statements about whether they are of the same or different color. Different color can be thought of as $2\pi/3$ (120°) phasal separation.

Chromatic state is the highest outer-most layer of W-state structure and exists exclusively in the sanctum. It furnishes a tubular topological structure that houses torsional state, which is an intermediate level of structure housing core dynamic state. In the chromatic domain, “toothpaste” equates to achromatic W-state, which has only the torsional and core dynamic layers.

Quarks

Quarks are the high priests of the inner sanctum. They are the greatest concentrations of mass (rest energy) in the Standard Model and are uniquely privileged in their ability to participate in all forces of Nature: electromagnetic, nuclear, and gravitational.

As massive repositories of energy, quarks seethe with dynamism. P-state mediation with nuclei is continuously a frantic struggle to enforce the imperative of cohesion against intensely powerful Coulomb repulsion. The cohesion imperative is the strong nuclear force.

Gluons

Gluons are the emissaries of the quarks. They are the W-state couriers that directly mediate strong cohesion. A simple combinatoric count shows there to be nine (9) combinations, consisting of a color designation and an anti-color counterpart. However, a null superposition implies a superfluous degree of freedom, reducing the effective number of combinations to eight (8). The null superposition can be thought of as equivalent to an overriding mandate for color neutrality in baryons.

Electromagnetic Transparency

The chromatic domain is figuratively sealed off from the secular exterior by a hard shell, loosely analogous to the ontic wall that separates the W- and P-domains. Like a cell membrane, it preserves a homeostasis of sorts in the sanctum. The membrane is completely transparent only to the electromagnetic force and gravitation, through which the interior and exterior domains interact freely and without inhibition.

Alpha Decay

The nuclear realm is replete with unrest and potential instability. Actual instability takes consequential effect in two primary ways, which are thoroughly well-known in nuclear physics. One is alpha decay, which can be thought of, figuratively, as a schism within the sanction. As biological analogy, it is akin to mitosis, wherein the inner contents split apart and go their separate ways. The parting, however, is sealed within the chromatic domain, and the diverging parts are encapsulated by membranes continuously throughout the entire process.

Beta Decay

Beta decay is analogous to an excommunication event, wherein energy content is expelled from the sanctum. The expelled contents, however, are downgraded to secular stature, as achromatic W-state. Excommunication is the ultimate head (in the hydrodynamic sense) of all electro-weak physics and is the justification for speaking of the weak *nuclear force*.

2.6.4.2 Genetic Analogy

In the 1860's, a lone bespectacled monk in Melk, then part of the Austro-Hungarian Empire, undertook a sustained empirical investigation of inheritance patterns manifest over multiple plant generations in a pea garden. His analyses and theoretical insights, which dealt with observable and unobservable concepts, were little known for nearly half a century, but they would become one of the most profound and lasting contributions to modern science.

The RQF finds Mendel's concept of *discrete phenotypic dominance* directly relevant to simplifying the picture and understanding of how quark properties combine.

Elimination of Fractional Charge

The conventional QCD reckoning holds that quarks have fractional charge. The *major quarks* (u, c, t) have charge $+2e/3$, and the *minor quarks* (d, s, b) have charge $-1e/3$. The fractional charge assignments are ungainly because they are *only* a bookkeeping device. $e/3$ is noticeable as a fraction of a fundamental constant of Nature, but whereas $\hbar/2$ ubiquitously crops up in anything having to do with fermions, $e/3$ has no physical relevance aside from quark bookkeeping.

Quark Combinatorics

The RQF enumerates the quark combinations by analogy to genetics:

Table 4: Quark Combinatorics: Mesons

Genotype	Phenotype
$M\bar{M}$	0
$M\bar{m}$	+1
$m\bar{M}$	-1
$m\bar{m}$	0

Table 5: Quark Combinatorics: Baryons

Genotype	Phenotype
MMM	+2
MMm	+1
Mmm	0
mmm	-1
\overline{mmm}	+1
\overline{Mmm}	0
\overline{MMm}	-1
\overline{MMM}	-2

For purposes of determining hadronic charge, the relevant genotypic information hinges only on the major (M) or minor (m) status of the quark constituents (*i.e.*, two echelons within the priesthood). The genotype is sufficient to determine the phenotypic outcome of net hadron charge, which is always an integer multiple of the electron charge magnitude, e .

It is observed that the phenotype is determined by a principle of discrete dominance similar to that in Mendelian genetics. Major (minor) quarks in the genotype equate to dominant (recessive) alleles. Physically, the P-state mediation within the sanctum has built-in preference for major quarks, which are conferred twice as much weight as minor quarks. The need to posit fractional charge is cleanly eliminated.

2.6.4.3 Nucleon Stability

Chromatic dynamism is the strong nuclear force, through which the priesthood strives to maintain cohesion directly through its W-state couriers, the gluons.

The chromatic domain is replete with micro-measurement events, and the resulting P-state mediation is extremely active in nuclei. It is frantically working to balance the competing grievances of the strong nuclear and electromagnetic forces among the quark constituents. This is an extremely complicated many-body problem, which makes nuclear physics the messy phenomenological subject that it is. A general statement, however, can be made about the P-state enforcement: It almost always succeeds in maintaining stability by enforcing baryonic three-ness, keeping the quarks grouped into protons or neutrons.

It so happens - or at least certainly seems to be, based on the evidence from the water tanks - that protons are stable, which is evidently emergent fact from the many-body problem setting. Neutrons are stable within nuclei, which is a contextually emergent outcome of their role as bit players in an overall P-state optimization strategy. Free neutrons, however, are not quite a long-lived optimum. After a trial-and-error process lasting on average about 15 minutes, the P-state mandate, by chance, hits upon an energy release solution, wherein a minor (down) quark transmutes to the major (up) echelon, excommunicating a W^- boson in the process.

2.6.4.4 Alpha Tunneling

P-state trial-and-error systematically discovers that alpha aggregations, consisting of two protons and two neutrons, are outstandingly stable configurations, expulsion of which can greatly reduce the unease buffeting heavy radioactive nuclei. The expulsion is more analogous to cellular mitosis than excommunication, as the products both remain encapsulated by a chromatic membrane.

Out in the open after release, the alpha captures two electrons, which jointly work themselves into a singlet configuration in what becomes atomic helium. The RQF is conducive to detailed visualization and quantitative modeling of how that process works out.

Gamow (1928) was the first to describe alpha radioactivity in terms of tunneling. The high-level concept is correct, but he went about it in what the RQF points out was a roundabout way that missed the essential nature of the underlying physics. In step with virtually all physicists of his time, he leveraged unitary dynamics and the Fermi Golden Rule of TDPT, which is arguably an extreme abuse of the mathematical machinery of conservative dynamic law. The RQF shows, instead, that tunneling is really the trial-and-error slowness of the P-state mandate hitting upon alpha expulsion as the most effective global strategy of relieving strain in the heavy nucleus.

2.6.5 Fundamentalization of the Forces

2.6.5.1 Dissent from GUT

The comprehensive architecture of W-state, which spans the entire scope of the Standard Model, is structurally rich and heterogenous. Each of the three fundamental forces (excluding gravitation) occupies a structural niche tailored to its specific nature. This amounts to *fundamentalization* of the forces, which signifies a radical rejection of GUT-style unification.

The RQF takes an aesthetic view toward beauty, unity, and symmetry in theoretic architecture that dissents strongly from prevailing sentiment, which holds symmetry in highest esteem and regards the quest for symmetry in

physical law as paramount. The quest for symmetry, as the chief aesthetic standard shaping judgment of whether proposed theories ring true, often comes at the cost of estrangement from real underlying physics.

The RQF, by contrast, is much more tolerant of compartmentalization within the comprehensive architecture. By its reckoning, four is not a bank-breaker; it sees no overriding prerogative for grand unification. It recognizes the cross-talk phenomenology that justified the GSW electro-weak unification, but it accommodates it under the joint parentage of the two forces, which are regarded as fundamentally different and distinct.

2.6.5.2 The Higgs Mechanism and Mass Generation

Redundancy of the Higgs Field

The conventional Standard Model uses the Higgs field and its interaction with particles to generate mass via spontaneous symmetry breaking. In the RQF, where mass is either a W -state attribute (for charged quarks, leptons, or electro-weak bosons) or a scalar appendage (for neutrinos), supposition of a separate field-based mechanism is redundant and antithetical to the ontology. The RQF rejects the Higgs field as a fundamental entity in its own right. Instead, the effects attributed to the Higgs mechanism – specifically, imparting mass to the W^\pm and Z^0 bosons – are interpreted as the energetic consequence of electro-weak cross-talk.

Boson Mass as Structural Cost

The W^\pm and Z^0 bosons acquire mass because they are the physical conduits of the P-state’s attempt to reconcile the competing demands of the electromagnetic (ω) and weak (L_z) forces. The mass is the structural energy cost incurred by the W-state as it mediates this cross-talk. Specifically, the W^\pm and Z^0 bosons possess a complex torsional state (defined by their $2t$ half-twists) that requires immense energy to maintain its transient, unstable geometry.

RQF Replacement of the Higgs

The role of the Higgs is absorbed by the P-state mandate itself. The P-state enforces the T_3 asymmetry (via the secondary twist) and dictates the necessary mixing angle (θ_W). The masses of the bosonic mediators simply reflect the amount of energy required for the P-state to implement the left-right splitting and the phase mixing. The Higgs “particle” is thus interpreted as a high-energy manifestation of extreme P-state stress – a transient resonance of the vacuum unease – rather than a distinct field excitation. Its properties are a signature of the energy ceiling for electro-weak cross-talk resolution, not the cause of mass itself.

2.7 Historical Alternatives

This section closes the first part of the Trilogy with assessments of the historical formulations of QT, in retrospect with the RQF in hand.

2.7.1 De Broglie-Bohm (dBB)

The pilot wave theory developed by De Broglie and Bohm (dBB) is a serious ontology proposal and realist theory through-and-through. It was an early forerunner of the RQF and a reasonable hypothesis about what the quantum world could be like.

2.7.1.1 Spectrum of Ontologies

dBB is actually a spectrum of ontology proposals:

- At the *wave-dominant* end of the spectrum, the mass-energy and dynamism is entirely in the wave, and the particle trajectory is an eikonal embedded in the wave structure. This one trajectory, whimsically called the *golden thread*, is uniquely endowed with special ontic status in that it predetermines the locus of wavefunction collapse, when the wave encounters a detector.

- At the opposite *particle-dominant* end of the spectrum, all of the mass-energy and dynamism is in the particle. The wave loses ontic stature and becomes merely an elaborate force law, encoded in the so-called quantum potential.
- At intermediate positions on the spectrum, wave and particle both have mass-energy and dynamism. This is mathematically the most elaborate and intricate case and the only one in which reciprocal interaction between wave and particle (*i.e.*, Newton’s third law) is *de rigueur*.

Hidden Variables Terminology

By convention, the wavefunction (wave-like part of the quantum state in dBB) is considered “overt” state because it is what traditional QT is accustomed to working with, whereas the particle-like part is considered hidden. That, however, clashes with two biases that favor particle ontology: (*i*) instrumentalist bias, because only particle-like phenomena are directly observed in experiments, and (*ii*) the linguistic slant of “pilot wave” in de Broglie’s original idea, which implies a subservient role for the wave. Practice is muddled, because the wave- and particle-dominant ends of the spectrum are often blurred together. On the one hand, practitioners applying dBB use wave-dominant formalism, which supplies the main mathematical machinery to derive the eikonal paths, but then they switch to particle-dominant on account of the biases.

Untenability of Particle-Dominant Ontology

the wave-dominant end of the spectrum is closest to the truth. The particle-dominant end is untenable for two reasons:

- If the wave is just an elaborate force law, the nature of the source and sourcing mechanism must be introduced and explained. It would presumably be novel and different from the very few types of forces recognized in conventional physics.
- Relativity requires a field-theoretic intermediary between source and particle, contradicting the claim that the wave loses ontic stature.

2.7.1.2 Assessment

dBB is not the answer. It fails because it is wrong about the character of the particle-like part (holism) of quantum state. It essentially replaces P-state with a single golden thread, but the golden thread is much too naive a mechanism to withstand the demanding requirements imposed by entanglement phenomenology. That much became subliminally apparent to Bohm himself, who struggled to make the quantum potential viable.

dBB, incidentally, is the only form of QT in which the two-slit experiment is more mysterious than the one-slit version. It is also noteworthy as the only body of quantum formalism in which real or imaginary parts are extracted.

2.7.2 Continuous Spontaneous Localization (GRW)

The continuous spontaneous localization (CSL) form of QT, originally developed by Ghirardi, Rimini, and Weber (GRW), to its credit, is the only historical alternative that takes Rule 2 seriously.

2.7.2.1 Limitations

GRW takes Rule 2 seriously, but only up to a point: It makes the mistake of treating collapse (spontaneous localization) as exceptional and a punctuation of Rule 1 dynamics, which remains the senior partner. In this respect, it is little different from standard QT.

dBB and GRW both fail because they are mechanistically naive; the only way not to be naive is the global coordination via P-state in the RQF. In GRW, the naivete is in the simple postulation of a certain density of collapse events per unit volume per unit time. That is deficient in two respects:

- The effects on the local W-state (*e.g.*, zbw kicks, narrowings) are determined by true innovation (untainted RNG output). They are thus uncorrelated with effects elsewhere in the quantum system and fail to implement the global coordination of the P-state mechanism.
- It only accounts for internally-triggered measurement events (zbw spontaneity) but not externally-triggered measurement events.

2.7.2.2 Epistemic Confusion

GRW accepts the orthodox premise that the wavefunction is epistemic, rather than ontic. That inevitably creates great confusion when trying to describe spontaneous localization and its implications. First, “physical collapse” is a misnomer. Second, heating is said to be a side effect of the localization, but then how can probability waves, if that is all that they are, generate heat?

2.7.2.3 Assessment

CSL, which represents the modern generalization of the GRW model, is conceptually powerful in its own right, transcending the mechanistic naivete and failure of GRW. It puts Rule 2 in proper perspective: In the microdomain, dynamism is a continuous interplay and tug-of-war between Rule 1 and Rule 2.

2.7.3 Many Worlds (MW)

2.7.3.1 Superposition of Macroscopic Classical Situations Untenable

We consider a highly simplified scenario, in which just one unique event in the history of the universe precipitates a bifurcation into two daughter universes. A student is in the laboratory and runs a silver atom through the Stern-Gerlach magnet. In one daughter universe (U), spin goes up - a factual outcome that quickly becomes entangled with the student’s brain state (perception and memory). In the other universe (D), the spin goes down, and the student perceives oppositely.

As time passes, the macroscopic divergence compounds: In U, the student goes through one sequence of arm movements, when he writes his lab report, to enter keystrokes ‘u-p’. In D, he goes through different arm movements to enter ‘d-o-w-n’.

The RQF demands clarity about what has happened: U and D both cohabit the same (3+1)-dimensional space. There are thus two distinct classical situations (ultra-wide equivalence classes of threads) of unlimited spatio-temporal extent that perpetually interpenetrate one another, without either being aware of the existence of the other. This cohabitation is simply not discussed in conventional presentations of MW. Like standard QT, MW does not demand where or when accountability.

The RQF maintains that this cohabitation is preposterous and cannot last. It is the exact same misunderstanding about superposition and durability of macroscopic classical situations that the Schrödinger cat highlights. Rule 1 primacy tells us that U and D, or live and dead cat, can coexist perpetually because it confers excessive authority and scope to superposition (Rule 1). The RQF, at this point, rules out and rejects MW as a serious proposal, because it gets the real physics wrong. Multi-situationality is not long-lived; it only takes root physically as ephemeral order.

2.7.3.2 Rule 1 Primacy

The MW pretense of being purely Rule 1 is transparently indefensible. It provides no mechanistic trigger to precipitate branching. It is forced to invoke the Born Rule to account for the irreversible dynamics unmistakably in front of our noses. The same critique applies to time-dependent perturbation theory (TDPT), which improperly overextends the Rule 1 Hamiltonian formalism to phenomenology that is plainly non-conservative and irreversible.

MW further suffers contradiction on the preferred basis issue. Not everything that can happen does happen, as we and our parallel brethren agree on the kind of measurement event that took place.

2.7.3.3 Lack of Complexity Control

And this is all before a word has been said about complexity getting out of hand!

2.7.4 Copenhagen

Bohr was right that the strangeness of the quantum world is for real and must be accepted, no matter how conceptually intractable or jarring. The RQF whole-heartedly embraces the strangeness but makes it intelligible, by rooting it in relational ontology. The RQF proves Bohr and von Neumann wrong on the core epistemic issue: It is possible to think non-classically.

Ironically, the RQF is closer to Copenhagen than the alternatives, in respects of overall simplicity and on the technical questions of absolute randomness and quantum jumps.

3 Quantum Gravity: Solution in the Realist Framework

This point marks the beginning of the second part of the Trilogy, which focuses on quantum gravity (QG) built upon the RQF and classical general relativity (GR).

3.1 Prelude to Quantum Gravity

3.1.1 Regime 1 as a Self-Contained Base

The five regimes of GR were introduced in Sec. 1.2.1. More can be said about Regime 1, now that the RQF has been developed.

3.1.1.1 Physics without Gravitation

Regime 1, as developed in Sec. 2, is physics without gravitation. It is the approximation, well-suited for most quantum experimentation in terrestrial settings, in which gravitation can be ignored. The space-time backdrop is then perfectly flat and Euclidean.

That is as it should be, because Regime 1 is a theory of the structure of matter-energy. It is the natural habitat and focal point of quantum physics and of the classical physics that emerges from it, at the macroscopic terrestrial scale of everyday life.

Accommodation of Newtonian Gravity

Physics without gravitation is slight overstatement. It would be silly to claim that the RQF scales up to and reproduces the classical physics of everyday life, only to find that apples do not fall. Newtonian gravity can be pulled in before broaching the formidable topic of quantum gravity (QG), but technically only if it is treated as an ordinary force and the Equivalence Principle is accepted as idiomatic.

At the end of our development of QG, the terrestrial physics of everyday life, fully inclusive of the QT of matter integrated with familiar classical physics, is reproduced as the full theory in the limit of $G \rightarrow 0$. The backdrop becomes virtually flat, and Newtonian gravity is restored. The Equivalence Principle, however, is rooted in fundamental principle (*i.e.*, gravitation as geometry) and not *ad hoc*.

3.1.1.2 Fact of Inertia as Idiomatic

With the assumption of a flat backdrop, the RQF comprehensively encompasses all of physics, all the way from quark up to the macroscopic terrestrial scale.

Structured Regression

The enterprise of science, wherein theory and experiment go hand-in-hand, can be regarded as a task of *structured regression*. Given the totality of empirical evidence, the RQF seeks to be the most parsimonious and powerful body of theory that fits the phenomenology with the greatest elegance, explanatory power, accuracy (interpolative efficacy), and predictive wherewithal (extrapolative efficacy). Parsimony means reliance on the fewest physical axioms, all of which should be heuristically reasonable and drawn from informed insight into the structure of matter in terrestrial settings.

Accommodation of the Fact of Inertia

However, the RQF, and even QG in the limit of $G \rightarrow 0$, relies on one physical axiom that defies rooting in any informed such insight. It is the fact of inertia (FoI), which was introduced in Sec. 1.3.1. Regime 1 can be considered a self-contained base, free of any cosmological input or conjecture, only if FoI is accepted as idiomatic (*i.e.*, unexplained and impervious to any deeper explanation). That, of course, is not at all unfamiliar; FoI is implicitly accepted as idiomatic whenever Newton's laws are applied.

QG proper technically falls short of cosmological scope and therefore also accepts FoI as idiomatic. Only when the origin of inertia (OoI) problem is addressed full-on does FoI cease to be idiomatic.

3.1.1.3 Neutrality on the Mysteries

Science, interpreted as structured regression, is primarily about getting the architecture and structure of physical theory right and then fitting parameters, as needed. Both aspects are guided by empirically informed insight based on first-hand observation of and experience with the subject matter at hand.

The RQF, as a structured regression, has some features and accommodations that it is unable to explain more deeply. Two simple examples illustrate the point. One is the fine structure constant, $\alpha \approx 1/137$, which has long attracted fascination. It is peculiar in that it is a dimensionless combination of fundamental constants, but the particular value of α is not rooted in pure mathematics.

A second example is the matter-antimatter asymmetry. The RQF, which honors full symmetry in fundamental physical theory to the greatest extent possible (and reasonable), is helpless to explain it from any first principles. Cosmological speculation is beyond its scope. Any application of the RQF must simply accept the asymmetry as idiomatic.

3.1.2 Adaptation of the Two Great Theories

The two great theories are setting out, figuratively, to construct a railroad line across the United States. GR begins on the east coast in Princeton, NJ. QT begins on the west coast in Berkeley, CA. Will they meet at St. Louis, or will one end up in North Dakota and the other in Texas? Do the great theories each have the internal resilience to meet the other halfway?

3.1.2.1 Background-Dependence of Conventional Quantum Theory

Conventional QT is paralyzed on the fundamental topic of time. It is well-known that it simply treats time as a parameter, without any deep understanding of it. The reasons are rooted in historical diffidence and fealty to Rule 1.

Non-Relativistic Treatment of Space-Time

Despite pretense that QFT is fully relativistic, conventional QT has always been diffident and fearful toward SR. It was subliminally realized early on, by Dirac and others, that unitary QM fundamentally does not sit well with $E = mc^2$, which was the central lesson of the zitterbewegung. The founders retreated, and quantum pedagogy took excessive - in fact, often exclusive - refuge in the non-relativistic low-energy regime.

To have focused on quantum physics in the low-energy regime, in which quanta counts and identities are reliably fixed, would have been a reasonable limiting of ambition, but the mistake was made of abandoning SR

proper (*i.e.*, Lorentz-invariance in the formulation of physical theory). It is perfectly sensible to insist that “non-relativistic” QM account for how an observer moving at relativistic velocity relative to a low-energy system would describe it, but traditional QT failed on that. The result was a rigid and inadaptable parametrization of time.

Timeless Cosmology

The problem of time in conventional QT was exacerbated by quantum cosmology in the 1960’s. Specifically, the Wheeler-DeWitt equation (1967), which took unitary dynamics to its farthest imaginable conclusion, had it that the quantum universe must be static and that time extinguishes itself. Some cosmologists, notably Barbour [1], in the face of the impasse, proposed timelessness as a grand all-encompassing metaphysical principle.

Loop Quantum Gravity

Loop quantum gravity (LQG) congratulates itself for weening itself from background-dependence, in contradistinction to string theory. However, it focuses on the Planck regime (Regime 5), which the RQF shows to be a theoretical curio fundamentally beyond experimental probing. LQG, like string theory, regards Regime 5 as where the keys to the kingdom for all further breakthroughs in fundamental physics lie. The RQF, by contrast, maintains that the investigation of QG must begin with how QT adapts to moderate departures from a flat backdrop.

3.1.2.2 Resilience of Realist Quantum Theory

Where? When?

There is no hope of QT being able to make contact with GR unless it can answer basic story-telling questions about time and space, *i.e.*, where? when? The RQF is ably well-equipped to do that, whereas conventional QT is not.

The RQF, unlike conventional QT, reveals the true significance of global time in Sec. 2.4.2.4, in which the time in the Schrödinger equation is shown to be a parametrization of spacing between rest manifolds. To the extent that simple problems in quantum physics are amenable to reductionist analyst (*i.e.*, such that small numbers of quantons can be treated as isolated systems), the global time in the equation, in practice, applies only to rest manifolds as they cut through the finite spatial vicinity of the laboratory. Global time, for all practical purposes in such settings, becomes local.

The RQF also reveals the true significance of the Hilbert vector, $|\psi\rangle$, *i.e.*, as a spatial distribution of W-state on a rest manifold. In conventional QT, by contrast, it is an opaquely abstract symbol that is not physically visualizable.

RQF Adaptation to Curved Backdrops

The RQF can readily be migrated to a curved backdrop, ultimately because it is much more of a classical kind of theory than conventional QM. The ontology of W-state, at the innermost layer of the chromatic full stack, consists of threads and spinors, which are flexible and truly local.

Aversion to Clarity

The conventional quantum mentality is its own worst enemy. Not only is it unable to answer questions about the spatio-temporal distribution of the wavefunction. It adamantly insists that such questions have no proper place in quantum physics, because the uncertainty principle (Sec. 2.4.1.4) is assumed to render them meaningless. The orthodox stance sabotages and preemptively suffocates any prospect of being able to make contact with GR.

3.1.2.3 Resilience of General Relativity

GR is a classical theory founded upon a clear unambiguous ontology. That, in and of itself, puts it on much stronger ground to be adapted than QM. GR depends on an underlying theory of matter only through the energy-momentum tensor, $T_{\mu\nu}$, in the Einstein-Hilbert field equations. It readily meshes if $T_{\mu\nu}$ is uni-situational, which is always the case when matter is modeled simply as a classical density distribution.

If $T_{\mu\nu}$ is multi-situational, on the other hand, it would pose very thorny complications for GR. Different curvature tensors in different classical situations would somehow have to cohabit the same arena, which is no longer unambiguous. The different situations would somehow have to be able to interfere meaningfully, despite a lack of ground rules.

That frightful prospect, fortunately, is averted in the QG unification, which is such that gravitation, arising from the QT of matter, is guaranteed to be uni-situation before it reaches effective scale.

3.1.3 Geometrodynamical Clock in Quantum Theory

The single most crucial and technically demanding test of whether QT can make contact with GR is the challenge of constructing a *geometrodynamical clock*, using the fundamental ontic ingredients of the theory. The clock provides an operational definition of local time, emergent from an underlying theory of matter.

3.1.3.1 Relational Framework

In preparing to approach QG, the space-time framework of Newton, Einstein, and Minkowski¹¹ must be superseded by a relational one, in which space and time obtain their meaning and properties only from context (*i.e.*, matter).

All physical theory, including GR, developed under the Newtonian framework proceeds from the premise of a flat space-time backdrop¹², which is held to be ontically primary in that its existence is independent of the presence or properties of matter. In this view, space-time *contains* matter and is regarded as a stage upon which the dynamism of matter continuously unfolds and plays out. That works well as a borrowed metaphysical concept in the conventional context of physics of isolated subsystems, but it is unsuitable for QG or cosmology.

The relational framework proceeds from a different set of premises, which instead takes as primary: (*i*) world lines, and (*ii*) light paths (more formally, *null geodesics*). World lines signify elemental trajectories of matter: (*i*) particle trajectories in classical mechanics, or (*ii*) long W-state threads in the RQF. They are subject only to the premise that they are shaped by some underlying system of physical law. The relational framework accepts as premise the topological structure of Minkowskian space-time, but not any quantitative measures of spatio-temporal distance.

3.1.3.2 Mystique of Time

In the conventional framework, time seems inherently more mysterious than space. Measuring rods are tangible, and spatial relationships are readily established from the mere existence of matter. The same is not true of intervals between clock ticks. On what basis, other than faith, can it be said that a second today is the same as a second yesterday?

Consider the extremely simple fiction of a universe consisting of just two particles that are perpetually still, not moving relative to one another. Space meaningfully exists in that a certain distance (d) separates the two, but if absolutely nothing changes, in what sense does time exist? If the particles exchanged light pulses with one another, then there would be a natural time standard, equal to d/c , against which to measure real dynamism and change. But if the particles went dark, would time suddenly cease to exist? Arguably no, because connections among points on the world lines made by light paths are considered real and meaningful, regardless of whether they are actually exploited.

That is the essential idea of the *geometrodynamical clock*. It is rooted in GR, but was missed by Einstein. It was not until its conceptual advent by Wheeler (1962) that the meaning of *duration* was demystified and satisfactorily explained.

3.1.3.3 Locally Emergent Time

The geometrodynamical clock can be regarded as an abstract operational definition of locally emergent time. The relational framework considers sequences of events on a world line (w) arising from their connectivity with events

¹¹It will be referred to henceforth, for brevity, simply as the *Newtonian framework*, as its essential features originated with him.

¹²The flat backdrop is the limiting case of weak gravitational fields - and ultimately the absence of matter.

on other lines via light paths. Those are maximally informative for lines that are infinitesimally close and parallel to w , as they amount to sustained event sequences that can be posited, in the simplest interpretation, to be linear. From the interleaving pattern formed by any two such sequences, the following two quantities become operationally well-defined: (i) ratios of distances between w and neighboring parallel lines, and (ii) ratios of durations between consecutive pulses in the two sequences. These respectively provide quantitative measures of spatial (geometric) and temporal (chronometric) relationships among world lines and events thereon.

3.1.3.4 Transcribing Quantum Theory to a Curved Backdrop

With the geometrodynamical clocking solution in hand, it remains to transcribe W-state onto a curved space-time backdrop (disregarding the source of curvature). The W-state dynamics, in free fall (*i.e.*, locally tangent to null geodesic), coincide with what has already been developed in Regime 1.

3.1.4 Cube of Fundamental Physics Theory

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 cube contains a set of eight *regimes of fundamental physics*, which are indexed as rows of a truth table. Each regime in the cube is encoded as three bits: ($G > 0$, $\hbar > 0$, $c < \infty$). $G > 0$ 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.

The cube is a simple and elegant way of representing RQG and the more familiar forms of physical theory that are limiting cases, wherein some bits are zero.

3.1.4.1 Fundamental Constants

Quantum gravity contains three fundamental constants: G (gravitational constant), \hbar (Planck's constant), and c (speed of light):

- c : The speed of light (c) originates in SR.
- G : The gravitational constant (G) originates in GR.
- \hbar : Planck's constant (\hbar) originates in QT.

Reißner-Schrödinger Claim about G

For a time a century ago, the fundamentality of G was thrown into doubt by the analysis of Reißner and Schrödinger. In their argumentation, they posited a universe of net energy zero (based on Machian mechanics), such that the total rest energy equates to the absolute value of the gravitational energy, *viz.*,

$$M_u c^2 \approx G M_u^2 / R_u \quad (57)$$

from which it follows that the gravitational constant, G , is related to the total mass, M_u , and size, R_u , of the universe, *viz.*,

$$G \approx c^2 \cdot R_u / M_u \quad (58)$$

Eq. 58 has the startling implication that G is not a fundamental constant of Nature, but rather, an emergent and potentially variable quantity that depends on the happenstance of the state of the universe.

Is G Fundamental?

G is known for being extremely difficult to measure precisely. Nevertheless, the empirical evidence of its constancy, over great stretches of cosmic time, is very strong. The RQF accepts the physical premise that G is indeed a fundamental constant of Nature, fully on par with c and \hbar . Acceptance of the premise logically requires rejection of the Reißner-Schrödinger analysis. Their argumentation relied on the net zero energy assumption of Machian dynamics, which is questionable and highly doubtful.

3.1.4.2 Octants (Approximating Theories)

Table 6: Cube of Fundamental Physics

Octant Number	$G > 0$	$\hbar > 0$	$c < \infty$	Brief Description
0	0	0	0	Classical mechanics with Newtonian gravitation
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	General relativity with $v \ll c$
5	1	0	1	General relativity
6	1	1	0	Non-relativistic quantum gravity
7	1	1	1	Relativistic quantum gravity

Octant 0: $G = 0, \hbar = 0, c = \infty$

This is the regime of non-relativistic classical physics. It is a limiting case of the RQF, with the technical nicety that it is also classical GR in the limits of $G \rightarrow 0$ and $c \rightarrow \infty$. For that reason, the equivalence principle, in all octants, is rooted in gravitation as geometry.

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

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

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

This signifies non-relativistic QT. 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 QM is pitched.

Technically, c does enter non-relativistic QM, but only through the fine structure constant, *viz.*,

$$\alpha \equiv \frac{e^2}{4\pi\epsilon_0\hbar c} \approx \frac{1}{137} \quad (59)$$

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.

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

This octant coincides with the RQF. In practical terms, it represents the widest range of physics phenomenology.

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

This is the non-relativistic limit of GR, in which all relevant speeds are small compared to the speed of light. It is a practical simplifying approximation of GR.

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

This is classical GR, which represents the pinnacle of classical physics, where the non-zerosness of \hbar is unimportant. In classical physics, matter-energy is assumed to be infinitely divisible, and the stability of matter is taken for granted.

Octant 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 is the curio octant, because it is doubtful whether any actual physics anywhere in the cosmos exemplifies this regime.

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

This signifies RQG, which is the most general case. It is the holy grail in the quest for quantum gravity.

3.1.4.3 Octant Operators and Terminology

Relationships between neighboring octants are formalized as bit-wise operators:

Table 7: Octant Operators

Operator	Operation
OR(1,0,0)	Gravitization
OR(0,1,0)	Quantization
OR(0,0,1)	Relativization
AND(0,1,1)	Degravitization
AND(1,0,1)	Dequantization
AND(1,1,0)	Derelativization

Quantization of Gravity?

Did Heisenberg and Pauli quantize gravity in their early 1929 foray into the topic? According to Tbl. 7, quantization means starting with classical GR and applying the OR(0,1,0) operator (*i.e.*, going from $\hbar = 0$ to $\hbar > 0$). And voilà, quantum gravity! But that was not what they did. They started with QM on a flat backdrop and applied quantization recipes to obtain gravitons as quantized excitations of a weak gravitational field.

What they actually attempted was gravitization, *i.e.*, starting in octant (0,1,1) and applying OR(1,0,0). They greatly underestimated the extreme difficulty of QG, and their methods utterly failed to generalize to Regime 3. Moreover, they were wrong about gravitons; they are not excitations of gravitational fields.

The RQF/TOE_f approach to QG is also a gravitization, but one that proceeds from a proper quantum foundation.

Dequantization

Does QT reduce gracefully to classical physics in the limit of $\hbar \rightarrow 0$? Conventional QT does not; it utterly fails because of its broken relationship with classical mechanics and electromagnetism. It has no equivalent of Newton's Second Law, and the Schrödinger equation, unlike Hamiltonian formalism of classical mechanics, is impervious to reverse engineering.

The RQF formally does reduce gracefully to classical physics in the limit of $\hbar \rightarrow 0$, but the result (unlike for derelativization) is not necessarily sensible. It revives the ultraviolet catastrophe and does not yield a stable theory of matter (which depends on the non-zerosness of \hbar).

3.2 Quantum Gravity in Regime 2

3.2.1 Scope of Regime 2

Regime 2 is the zone of moderate gravitational strength, such that the linear approximation of classical GR holds.

3.2.1.1 Governing Dynamics of GR

GR is ultimately a simple subject in that it comes down to two dynamic entities and governing equations, which are easy to understand qualitatively.

The entities:

- **Mass-Energy:** Mass-energy is the totality of *dynamic content* of the universe. W-state, rooted in the QT of matter in Regime 1, is its ultimate fount.
- **Curvature of the Backdrop:** Space-time, in classical GR, is relational and dynamic (*i.e.*, can depart from Euclidean flatness). Curvature is formalized in the field tensor, $h_{\mu\nu}$.

The equations:

- **Sourcing Equation:** The sourcing equation, also known as the field equation, accounts for how the curvature is shaped by the presence of matter-energy. The influence of matter-energy is funneled through the energy-momentum tensor, $T_{\mu\nu}$.
- **Kinematic Equation:** The kinematic equation accounts for how matter-energy is affected by the gravitational field, $h_{\mu\nu}$. The field establishes a local illusion of free fall, which has all appearances of an equivalence class of inertial frames. Regime 1 physics holds in any inertial frame of the free fall.

This is well-trodden subject matter in many excellent textbooks and will be familiar to experts.

3.2.1.2 Linear Approximation

In the linear approximation of GR, gravitational self-energy is ignored. It follows that the energy-momentum tensor, $T_{\mu\nu}$, is sourced *entirely* by Regime 1 W-state and is therefore of purely quantum origin. The sourcing and kinematic equations are then a closed-loop pair of reciprocal dependencies.

3.2.1.3 Uni-situationality

GR can survive contact with QT only if the uni-situationality of the energy-momentum tensor, $T_{\mu\nu}$, and the field tensor, $h_{\mu\nu}$, is preserved. The RQF/TOE_f will enforce the uni-situationality as the outcome of a non-local P-state mediation process, involving large widely-distributed aggregations of matter-energy.

3.2.2 Origin of Gravitation

In the QG context, the principal challenge in Regime 2 is to explain the *origin of gravitation*, *i.e.*, how uni-situational $T_{\mu\nu}$ arises from the quantum theory of matter at microscopic level.

3.2.2.1 Net Energy of Microscopic Matter

Consider a general scenario consisting of N microscopic masses (for simplicity, all equal to m) that are moderately or widely separated. The net energy of the configuration is equal to

$$E = Nmc^2 - \sum_{i<j} \frac{Gm^2}{r_{i,j}} \quad (60)$$

The first term on the right-hand side of Eq. 60 represents all self-energy accounted for in Regime 1. The second term is the gravitational energy of the configuration. We further simplify Eq. 60 by considering only the average inverse distance between the masses, *viz.*,

$$E = Nmc^2 - \frac{1}{2}N(N-1)Gm^2/r \quad (61)$$

in which r is the inverse of the average inverse separation.

3.2.2.2 Planck Minimum

Eq. 61 can be rewritten in terms of the Planck mass, M_P , and length, L_P , *viz.*,

$$E = Nmc^2 \left[1 - \frac{1}{2}(N-1) \left(\frac{m}{M_P} \right) \left(\frac{L_P}{r} \right) \right] \quad (62)$$

The Planck mass is given by the equation:

$$\frac{GM_P}{c^2} = \frac{\hbar}{M_P c} \quad (63)$$

whose left- and right-hand sides respectively represent a Schwarzschild radius and a Compton wavelength. Both values equate to the Planck length.

Eq. 63 indicates that M_P is the quanton mass whereat the compressibility limit of the W-state, represented by the Compton wavelength, is on the verge of being crushed by ultra-strong gravity. In short, it represents the largest physically realizable quanton mass. It thus imposes an upper bound on the number of tiers that can be realized within the Standard Model, but indirectly because gravity is technically extrinsic¹³ to the SM.

It is henceforth assumed that $m < M_P$ and $r > L_P$, both inside and outside the event horizon. That is, quantons are not crushed by their own mass, and the W-state compressibility limit holds. Two important consequences then follow from Eq. 62:

- The gravitational term in Eq. 62 is appreciably non-zero only if Nm/M_P is at least on the order of unity. That is, the Planck mass represents the smallest aggregation of quanton masses that can collectively gravitate.
- In order for the net energy to decrease toward zero but stay positive, L_P/r must vary inversely with N . That is, as matter undergoes extreme gravitational compression, r must be enlarged substantially beyond L_P .

3.2.2.3 P-state Mandate

Conventional thought and anticipation holds that the the domain of overlap between QT and GR is exotic and extreme, because there are few realms of phenomenology (represented by octants 6 and 7) in which \hbar and G both figure importantly in the local physics of W-state. That is true, but it does not at all follow that quantum physics plays no role in gravitational or cosmology. Instead, quantum physics arises through P-state mediation, which is always continuously at work because matter-energy is always buffeted by micro-measurement activity.

Mass Quorum

The P-state mandate is to minimize net energy throughout the universe, but in a way that preserves the local illusion of free fall (provided that matter-energy locally follows geodesic paths). The optimization strategy depends on finding a *quorum* of microscopic masses. The quorum size is N , such that second term in the square brackets becomes appreciably non-zero. As was noted, this requires total mass on the order of M_P times the averaged L_P/r , which is always greater than unity. The quorum gathering is the sourcing mechanism that ultimately represents the *origin of gravitation* from microscopic matter-energy.

¹³The statement in Sec. 2.6.2.2 that the number of tiers is a “soft provisional” number technically still holds.

Non-Local Sourcing

Newton and Einstein were both worried about spooky action at a distance. The RQF/TOE_f vindicates both concerns and shows that Nature really is *spukhaft* in both respects. Non-local P-state mediation explains entanglement phenomenology in Regime 1, and it also explains gravitational sourcing in Regime 2.

The quorum gathering in Eq. 62 can be sourced locally or non-locally. Local sourcing occurs in matter-rich regions of the universe, which aptly describes the solar system and certainly all terrestrial settings. A quorum of nearby masses is at hand. The equations of classical GR apply in original form, without need for MOND adjustments, and GR reduces to a local field theory of the familiar kind.

The situation is substantially different when quora cannot be sourced locally. This happens both within the observable universe at the outer fringes of galaxies and at the little-known outer fringes of the cosmos. In both settings, matter-energy is extremely diffuse and far-flung. The P-state must then work over vast distances to effect the grand strategy of energy minimization.

3.2.2.4 Enforcement Action

What does the P-state mediation actually do? What actions does it effect? The short answer:

- From the sampling of matter-energy across the cosmos, the P-state infers a uni-situational $T_{\mu\nu}$, which is a smooth energy-momentum tensor that is locally well-defined, but varies coarsely over the spatial expanse of the rest manifold.
- The P-state implements $h_{\mu\nu}$ adjustment globally across the manifold. It too is uni-situational and locally well-defined, but varies coarsely over the spatial expanse of the rest manifold in fashion congruous with $T_{\mu\nu}$, as required by the sourcing equation of classical GR.
- As $h_{\mu\nu}$ represents space in relational terms, no local W-state experiences any fitful displacement. The illusion of local free fall is continuously maintained.

If the spatial extent of the quorum is small compared to the scale of the smooth classical variation in $T_{\mu\nu}$ and $h_{\mu\nu}$, the classical GR premise of local field mediation suffices to account for dynamic change in $T_{\mu\nu}$ and $h_{\mu\nu}$. In that case, there is no need to posit any non-local mechanism. That ceases to be the case, however, if the quorum must be sourced over vast distances.

The adjustment processes for $T_{\mu\nu}$ and $h_{\mu\nu}$ is extremely efficient. Because the quorum size, N , is extremely large except in the close vicinity of the Planck regime, it does not take at all long for the P-state to find the steepest descent path toward energy minimization. The time constant is the Planck time, T_P , which is stupendously tiny. The adjustment mechanism is therefore, for all practical purposes, instantaneous.

3.3 Quantum Gravity in Regime 3

3.3.1 Scope of Regime 3

Regime 3 is the zone of strong gravity, such that nonlinear effects, such as manifest in classical GR, become appreciable.

3.3.1.1 G-state

In Regime 3, we reckon with the fact that gravitational field itself is a repository of energy. It is the energy of geometric stress resulting from curvature (*i.e.*, deviation from Euclidean flatness). This is formalized in the RQF/TOE_f as third type of ontic state, alongside W-state and P-state. Whereas W-state and P-state are of quantum origin, G-state is rooted in the dynamism of space-time itself.

3.3.1.2 Additive Combination and Feedback

G-state is similar to W-state in that both are fundamentally local entities. They jointly embody all physicality in the universe, and their dynamics appear to be local, as far as any agent of local physics can tell.

W-state and G-state have the important property that they combine additively. That is the crucial property, without which the nonlinearity of classical GR, beyond Regime 2, could not be reproduced.

The task of QG in Regime 3 is two-fold. The first is to develop and implement the concept of G-state, which consists of three sub-tasks:

- Formalizing G-state as an ontic entity and showing how it derives from $h_{\mu\nu}$.
- Formalizing the additive combination of W-state and G-state.
- Showing that the sequence of W-state and G-state adjustments, arising from higher-order nonlinear feedback, is convergent, resulting in closed-loop nonlinear solutions.

3.3.1.3 General Invariance

The second task of QG in Regime 3 is to ensure that *general invariance* is preserved. General invariance is a top-level architectural feature of classical GR, which makes the full nonlinear theory self-constructing, *i.e.*, derivable in full mathematical detail from an elegant minimum of axioms formalizing the equivalence principle and generalization of SR.

3.3.2 Unification of General Relativity and Quantum Theory

3.3.2.1 Achievement

The two great theories have been intermeshed and shown to interoperable. This is it! GR and QT have been unified. The locus of unification was primarily in Regime 2, in tackling the origin of gravitation. It was shown that the Planck mass, Compton length, and quorum sourcing are central concepts. The closure is in Regime 3, with the introduction of G-state and its additive combination with W-state.

The unification is astonishingly easy, once a good realist QF solution is in hand. Moreover, it demonstrates that the locus of unification is in not in the Planck extreme (Regime 5), but instead, in Regimes 2-3, which are familiar and within testable reach.

3.3.2.2 Odd-Couple Opposites

The unification confirms that the two great theories remain odd-couple opposites, as noted in Sec. 1.2.3. QT and the classical physics that derives from it reigns in octants 0-3. GR reigns in octants 4-5. Octant 7 applies only in the Planck regime, and octant 6 is purely curio.

3.3.2.3 Scope and Prediction Potential

QG technically falls short of cosmological scope, as its solution involves only ontic ingredients (W-, P- and G-state) of the observable universe and their governing dynamics. However, the non-local quorum sourcing mechanism does point to insights and potential solutions for outstanding problems at galactic scale (*i.e.*, the dark matter conundrum) and cosmic scale (*i.e.*, the origin of inertia).

3.4 Quantum Gravity in Regime 4

Regime 4 encompasses the physics of ultra-strong gravity, featuring black holes and event horizons. While the core QG unification is achieved in Regimes 2 and 3, black hole phenomenology serves as crucial testing ground, where the limits of the G-state geometry precipitates conflict with the information content of W-state.

3.4.1 Black Holes as G-state Domination

In Regime 4, the G-state (geometric stress) becomes overwhelmingly dominant. The P-state mandate to minimize energy produces local environments where the gravitational potential is so immense that it structurally overpowers the self-energy of the W-state.

3.4.1.1 W-state Compression and Degeneracy

As matter passes the event horizon and continues falling toward the singularity, the W-state is subjected to extreme compression. The W-state structures (*e.g.*, threads, twists, zbw) are compressed toward their theoretical limit defined by the Planck mass. However, the RQF/TOE_f posits that the W-state retains its fundamental ontic structure right up to the singularity (*i.e.*, all the way through Regime 4). The final state of matter is an extremely compressed and highly degenerate W-state, whose original information content becomes encoded in the geometry of the compression itself.

3.4.1.2 The Event Horizon as a P-state Boundary

The *event horizon* is not a physical barrier but a P-state boundary condition. It defines the region where the gravitational stress (G-state) is so strong that the local time constant of the P-state's mediation process approaches infinity relative to a distant observer. Information is not lost; rather, the W-state dynamics slow down to an apparent halt from the outside, preserving the RQF/TOE_f's core principle that information (W-state structure) is never destroyed.

3.4.2 Resolving the Information Paradox

The conventional *information paradox*, stemming from the conflict between the QM requirement for unitarity and apparent destruction of information swallowed by black holes, is dissolved within the RQF/TOE_f.

3.4.2.1 Information is Ontic Structure

Information, in the RQF/TOE_f, is the ontic geometric structure of the W-state. Since the P-state mandate is continuous and global, and since W-state is never destroyed (only highly compressed) the information remains encoded in the geometry of the singularity.

3.4.2.2 Hawking Radiation as P-state Leakage

Hawking radiation is reinterpreted as a form of P-state energy leakage from the highly stressed geometric boundary of the event horizon. The P-state, in its continuous attempt to enforce the equivalence principle across the horizon, generates momentary, localized instabilities (virtual particle pairs) at the boundary. This radiation is sourced by the G-state's immense energy, carrying away the geometric stress, but not the original W-state information of the collapsed matter. The black hole shrinks, but the information is held by the remaining singularity until the black hole fully evaporates, where the residual information is released through the terminal phase of the P-state's global balancing act.

3.4.3 Gravitational Radiation

3.4.3.1 Detection

Joe Weber's career represents the application of the full resources of 20th-century physics - intellectual and technological - to the detection of gravitational waves. Would any of his detectors have stood a chance? The short answer is no.

Detection of gravitational waves was finally achieved by LIGO (Laser Interferometer Gravitational-wave Observatory) in 2016. It was technologically superior to Weber's detectors in three key respects:

- **Precision and Scale:** LIGO utilized Fabry-Pérot interferometers with 4-kilometer arms, offering dramatically greater path length than Weber’s 1-2 meter resonant aluminum bars. The scale difference was key to making the miniscule strain measurable.
- **Noise Reduction:** LIGO achieved extraordinary isolation using seismic isolation stacks and operating in a high vacuum. Weber’s simple bars were highly susceptible to terrestrial noise.
- **Time-Coincidence:** LIGO used two widely separated detectors (one in Hanford, WA, the other in Livingston, LA) to confirm the gravitational origin of the signals and reject local noise. For these types of reasons, Weber’s claims of detection could not be independently verified, and all known attempts were unsuccessful.

In hindsight, the detector designs of Weber and Braginsky were based on certain misconceptions about how gravitational waves would actually become manifest. Weber’s bars were sensitive to amplitude, whereas the strain ($h_{\mu\nu}$) predicted by GR was better measured by LIGO’s differential path length change.

3.4.3.2 Status of the Graviton

What is the RQF/TOE_f word on gravitons? The answer is two-fold:

- Gravitons are *not* excitations or lumped aggregations of the G-state itself. The G-state is geometric stress, not a field-theoretic manifestation of fundamental particles. They therefore have no proper place in the Standard Model, which is purely an inventory of W-state types.
- The LIGO detector, however, does register quantized parcels of incoming energy. Those quantal lumps are the only observable phenomenology and realizations of the long-fabled gravitons. To the detector, they do indeed have spin $2\hbar$ and travel at the speed of light, consistent with the notion of a classical wave as a quantum energy carrier. The graviton is thus a manifestation of *quantized energy transfer* between G-state and W-state (of the detector), but not the ontology of the G-state itself.

3.4.4 Inside Black Holes

What happens inside black holes, beyond the event horizon, is mystery and speculation. We can never know for sure, because no signal can escape the tug of gravity. However, some inferences are possible, providing some insight into what Regime 5 is like physically, as the final hold-out against literal singularity.

How many microscopic masses can fit inside a Schwarzschild radius? The Schwarzschild radius, R_s , is equal to:

$$R_s = NGm/c^2 \tag{64}$$

in which N is the number of masses, all of amount m . A volumetric estimate of N is obtained from:

$$N = \frac{4}{3}\pi R_s^3 / r_{\min}^3 \tag{65}$$

in which it is assumed that the microscopic masses are packed into cubic volumes of edge length r_{\min} . Substituting Eq. 64 into the right-hand side of Eq. 65 and using Eq. 63, we find:

$$\frac{4}{3}\pi \cdot N^2 \left(\frac{m}{M_P} \right)^3 \left(\frac{L_P}{r_{\min}} \right)^3 = 1 \tag{66}$$

which implies that $N \gg 1$ if $m \ll M_P$ and $r_{\min} \approx L_P$. However, the ratio m/M_P is not overwhelmingly small, which indicates a moderate value of N satisfying Eq. 66, belying the notion of black holes as endlessly voracious sucking machines.

This analysis suggests that r_{\min} must increase to offset growth in N , while m/M_P is fixed. Alternatively interpreted, the actual volume that quantons stake out for themselves once inside the event horizon increases greatly beyond L_P , suggesting a bulwark against singularity.

Singularity Resistance

The thread structure of the W-state of ingested matter is the bulwark against literal physical singularity. The P-state mandate to preserve W-state stability means it enforces a minimum volume per quanton even under nearly infinite G-state stress. The $h_{\mu\nu}$ adjustment cannot shrink the space to zero because that would destroy the W-state structure and thus violate the ultimate mandate of energy minimization, which includes the W-state self-energy.

Regime 5 is the region inside the Schwarzschild radius where N and m are forced to satisfy Eq. 66 by increasing r_{\min} beyond baseline values that apply at lower energy. In this regime, the P-state's effort to preserve W-state structure is maximal. The literal singularity is superseded by the maximally compressed W-state structure, creating a core in which the $T_{\mu\nu}$ and $h_{\mu\nu}$ are mutually coupled at the Planck limit. This core is the true end-state of matter in the RQF/TOE_f, not an infinite density condition.

3.5 The Dark Matter Conundrum

Classical GR has been splendidly vindicated throughout the observable universe, except at galactic fringes. There, the the observed stellar velocities at the outer ends of the spiral arms substantially exceeds what classical gravitational theory predicts, on the basis of head counts of optically detectable matter sources. Modified Newtonian Dynamics (MOND) is invoked as a phenomenological patch to pad over the discrepancy.

3.5.1 Differing Explanations

Much has already been said in Sec. 1.4 and will not be repeated. Some key points, however, are now much clearer, having the QG solution in hand and appreciating its capacity to support non-local action at a distance.

3.5.1.1 Shortcomings of Classical GR

The dark matter (DM) conundrum does expose a real shortcoming of classical GR, which, as a classical theory (*i.e.*, not informed by quantum insight), is necessarily a local field theory. That makes it fundamentally ill-equipped and wrong vis-à-vis non-local quorum sourcing at the galactic fringes, where matter is extremely diffuse and far-flung. The RQF/TOE_f maintains that non-local quorum sourcing is a real phenomenon and at the heart of the DM conundrum.

The failure of GR, in this respect, is not at all a call to scrap the great theory and to replace it with something radically different and incompatible with it (*e.g.*, MOND as a graft onto fundamental theory). The QG augmentation of GR fully preserves its classical ontology and governing equations in their original forms, but it disowns the premise of strict local causality in the dynamics. The QG augmentation injects non-local correlations into the $T_{\mu\nu}$ and $h_{\mu\nu}$ updates, but in a way that preserves the illusion of local free fall.

3.5.1.2 Obviation of Exotic Matter Sources

Prevailing belief holds that the DM conundrum stems from a failed head count, in which the missing heads belong to exotic forms of matter alien to the Standard Model. The RQF/TOE_f rejects that and maintains that QG, on a solid realist footing, comes to the rescue. There is no need to suppose new forms of matter; the SM inventory of quanton types stands complete (other than the allowed generalizations based on higher-order torsion numbers).

3.5.2 Testing Criteria

Claiming resolution of the DM conundrum is high-stakes and ambitious. It requires substantial further investigation on two fronts, one theoretical and one observational.

3.5.2.1 Theoretical Criterion

The theoretical contention of the RQF/TOE_f is that the high stellar velocities at the ends of the outer galactic arms is a manifestation of overall P-state optimization strategy not predicted or countenanced by classical GR. The theoretical challenge is to come up with a reasonable quantitative model of a hypercubic PDF for P-state

mediating non-local W-state dynamics across a galaxy model. It would have to show that the excess velocities at the fringe are indeed the outcomes of a grand strategy of energy minimization.

3.5.2.2 Observational Criterion

With a reasonable and viable galactic P-state model in hand, the next challenge is to show that the full galactic model, comprehensively encompassing W-, P-, and G-state, can be fitted to available observational data, such that unique falsifiable predictions of the outer velocities can be made. The observational data, of course, consists only of optically detectable bodies of matter. If predicted velocities match observation, it would be a big catch and vindication of the RQF/TOE_f.

4 Origin of Inertia: Solution in the Realist Framework

This point marks the beginning of the third part of the Trilogy, which focuses on the origin of inertia (OoI), moving the RQF/TOE_f into an explicitly cosmological scope.

4.1 Scope

The OoI problem, which seeks to fathom the physical explanation of the fact of Inertia (FoI), is central to finalizing the RQF/TOE_f. The capacity of the QG solution to support non-local action at a distance is central to solving the OoI problem, just as was the case for the DM conundrum. As before, key points are now much clearer with the QG solution in hand.

4.1.1 QG as an Extended Self-Contained Base

QG can be regarded as an extension of the RQF to the observable universe, across all regimes of gravitational strength. As a structured regression, it is a feedforward structure, layered by the GR regimes. However, QG falls short of cosmological scope (as it should). As such, the fact of inertia (FoI) remains idiomatic, *i.e.*, treated as a necessary but unexplained input for the physics of Regime 1.

4.1.2 Cosmology Agenda

The final part of the Trilogy signifies the leap toward an explicitly cosmological scope for the RQF/TOE_f, in that the OoI problem requires consideration of all matter-energy in the cosmos.

Embarking on cosmology, by any reckoning, is a grand and ambitious undertaking, but it must start by addressing and setting out to solve two key problems of cosmological origin that are pervasively apparent in everyday terrestrial life:

- **Origin of Inertia:** Why is it that some reference frames are inertial but others are not? Why is it that any two inertial frames are related to one another through relative motion at constant velocity?
- **Olbers' Paradox:** Why is the sky dark at night?

Only the first of these will be addressed. The OoI problem is to cosmology what quantum foundations (QF) is to quantum physics.

4.1.3 Sealing the Bottom of Physics

The scope now is quark to cosmos, quite obviously an extremely great dynamic range of scale. The upper end of the spectrum is open-ended, but the same is not true of the lower end. Quark phenomenology represents the smallest spatial scale that is experimentally reachable and at which physical theory is well-tested and firmly established. Yet string theory and LQG are plumbing depths some 20 orders of magnitude below quark scale, based on the supposition not only that there is real physical ontology down there but also that it is the only way to make logical sense of everything upstairs!

The RQF/TOE_f maintains that physics must be sealed at the bottom below quark scale, unless experiment turns up new phenomenology calling for physical theory to be opened down further. The smooth continuous space-time of GR can then be preserved throughout the entire dynamic range. This represents a radical divorce from string theory and LQG, which maintain either that we vastly underestimate the dimensionality of space-time or that its very structure needs to be shredded.

4.2 Non-Local Solution of the Origin of Inertia

4.2.1 Shortcoming of Classical GR

The OoI problem, like the DM conundrum, exposes another real shortcoming of classical GR. This second shortcoming also stems from the flawed premise of strict local causality mediated entirely by W-state and G-state.

Under the supposition of strict locality, classical GR is not strong enough to supply the cosmic gravitational influence needed to solve the Machian dynamics problems (*e.g.*, to make the water in the bucket rotate). Cosmic gravitation is analogous to the violation of the Bell inequalities, which preclude strong entanglement phenomenology.

4.2.2 The Relativistic Inertial Field

The P-state provides the necessary non-local action to solve the OoI problem by creating a universally constant, relational field structure.

4.2.2.1 Inertia as P-state Resistance

The FoI is the measurable resistance of a W-state to changes in its state of motion (acceleration). This resistance arises from the P-state mandate to maintain the coherence and energy minimization of the W-state relative to the entire cosmic mass quorum. When a local W-state is accelerated, the P-state must instantaneously perform a massive, non-local realignment effort to adjust the geometric arrangement of the surrounding inertial field (*i.e.*, the G-state generated by the quorum). The FoI reflects the locally observable cost of this instantaneous global realignment.

4.2.2.2 The Cosmic Inertial Frame

The P-state, operating globally to minimize energy (Sec. 3.2.2), naturally defines a preferred cosmic rest frame - the global P-state rest manifold - which minimizes the total gravitational potential energy of the universe. It can be thought of as a weighted average of the rest frames of the distant matter in the cosmos. Any local acceleration is measured relative to this cosmic frame, resulting in Newton's Second Law ($F = ma$). This constitutes the quantitative realization of Mach's Principle in the RQF/TOE_f.

4.2.3 Falsifiability

The RQF/TOE_f solution of the OoI is falsifiable. Any detection of inertial effects that are provably local and independent of the cosmic mass distribution would invalidate the solution.

4.2.4 Structured Regression with Feedback Loop

With the OoI solved, the structure of science takes dramatically different form. The solution shows FoI, hitherto accepted as idiomatic, to be an instance of analytic redundancy, *i.e.*, no longer an independent degree of freedom in the cumulative body of empirical fact. Removal of this redundant degree of freedom, however, dramatically changes the form of the structured regression that the body of theory now becomes:

- **Cyclic Structure:** It is no longer a feedforward structure (wherein FoI is axiom), but a cyclic structure. W-state dynamics drive P-state action through Rule 2, which determines G-state geometry (*i.e.*, gravity and inertia), which in turn affects W-state dynamics (*i.e.*, geodesics and local causality).

- **Final Theory:** The RQF/TOE_f is the most parsimonious, elegant, and powerful theoretic structure that best fits the slimmed-down body of non-redundant empirical fact.

4.3 Wheeler-DeWitt Equation

In the RQF/TOE_f, the Wheeler-DeWitt (WdW) equation is demoted from a fundamental law to a mathematical relic that describes the Rule 1 evolution of the W-state only, explicitly excluding the necessary Rule 2 selection mechanism.

4.3.1 WdW: The Ultimate Expression of Rule 1 Primacy

The WdW equation, derived by applying canonical quantization to GR, attempts to describe the wavefunction of the entire universe, $\Psi_{\text{univ}}(h, \Phi)$, where h is the metric of 3D space and Φ is the matter field. The equation is famously problematic because it suffers from the problem of time: $H|\Psi_{\text{univ}}\rangle = 0$. Since the Hamiltonian must equal zero, the equation that Ψ_{univ} is static and timeless. This is the ultimate logical conclusion of attempting to apply a purely unitary (Rule 1) description to the evolution of the universe.

4.3.2 Exclusion of P-state

The RQF/TOE_f holds that the WdW equation fails because it represents an incomplete ontology. It describes only W-state dynamics but completely omits P-state. As far as that goes, it is a mathematically correct description of the unitary evolution of W-state across the space of all possible 3D geometries (or superspace, as it was called). However, because the RQF/TOE_f defines time as the rate of change of the W-state structure, which is enforced by the P-state's constant Rule 2 selection. The WdW equation thus describes a physically impossible state. It forbids change, and therefore also necessarily forbids the existence of time. The physical universe must follow the path selected by the P-state, which is non-unitary and time-evolving (consistent with the Friedmann equations).

In conclusion, the WdW equation is an elegant, but ultimately empty, mathematical expression of the W-state's unitary potential, failing because it does not include the P-state mechanism that defines a real, evolving, uni-situational universe.

4.4 Conclusion

The completion of the origin of Inertia (OoI) solution (Sec. 4.2) marks the closure of the RQF/TOE_f. The theory now provides a comprehensive, unified, and ontologically consistent framework from quark to cosmos.

4.4.1 Redundancy of the Fact of Inertia

The core achievement of Sec. 4 is the demonstration that the fact of Inertia (FoI) - long treated as an unexplained idiomatic axiom in Regime 1 - is analytically redundant. It is shown to be a direct measurable consequence of the P-state mandate of global energy minimization (the **OoI** solution). Inertia is the resistive force generated by the entire cosmos (G-state geometry) when a local W-state attempts to accelerate relative to the preferred cosmic rest frame of the P-state.

4.4.2 The Final Structure

The removal of the FoI as an independent axiom transforms the structure of the theory from a feedforward hierarchy to a closed cyclic structure:

- **Quantum Foundations (W-state, P-state):** Defines the ontic structure and dynamism of matter-energy ($T_{\mu\nu}$) and locally emergent time.
- **Quantum Gravity (G-state):** The global cumulative action of the P-state generates the space-time curvature ($h_{\mu\nu}$), which embodies both gravity (local) and inertia (cosmic).
- **Feedback Loop:** The resulting G-state geometry dictates the inertial path (geodesic) of the W-state, closing the loop and eliminating the need for an independent law of motion (FoI).

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