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Original Paper

Beyond Wave-Particle Duality: The Wave Energy Exchange (WEX) Principle and the Intrinsic Wave Nature of Matter

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Abstract: Classical physics was built on a 'particle view' of matter where fundamental entities were assumed to be tiny indivisible structures with objective properties and permanent existence, a view that lasted from the earliest days of scientific thought until the 1920s when experiments and theories began exposing a wave aspect of matter. This led to the 'wave-particle duality' view where fundamental entities are believed to have both wave and particle properties, the default view that holds to this day despite numerous mysteries and paradoxes that remain unresolved.

The paper argues for a third possibility, that the intrinsic nature of matter is not particle-like, not wave-particle-like, but purely wave-like. The claim is stated as a principle:

> ***The Wave Energy Exchange (WEX) Principle:*** *(i) The sole persistent constituents of physical reality are spatially extended energy waves that can exchange energy with other waves, interfere and/or unify with them, and dynamically evolve in our space and time universe. (ii) Particles with precise property values are point-in-time signatures of quanta of energy emitted by an energy wave and absorbed by a measurement device.*

Part (i) is supported by the features that quantum formalisms share. Eleven formalisms are explored which differ significantly in the central objects they use to model fundamental entities and in the abstract mathematics used to make predictions. Yet every formalism directly represents or predicts the same eight features of fundamental entities. The paper treats the features that stay fixed across formalisms as a more defensible guide to the ontology of fundamental entities, whereas extrapolating the mathematics of any given formalism leads to vastly different ontologies which often conflict with one another. The paper imposes a single constraint on its reading of the shared features across formalisms, spatiotemporal realism, which requires fundamental entities to physically exist in the three spatial dimensions and time of our universe where physicists and their measurement devices also exist. Under that constraint the shared features collectively suggest the wave aspects of matter are persistent in time while the particle aspects are fleeting, appearing only at the moment of measurement. The wave realism ontology asserted in the principle is therefore a conclusion of the analysis, not an additional assumption.

Part (ii) matters because most quantum mysteries arise from mathematics, interpretations, and terminology that remain grounded in the assumption that particles are fundamental constituents of our physical reality while attributing little-to-no ontological status to the wave aspect of matter. Physicists speak of particles in superposition existing in multiple places simultaneously, particles having hidden properties when not being measured, wave functions collapsing from many possible

particles in superposition to one actual particle when measured, entangled particles influencing one another at a distance, and so on. These particle-centric perspectives and terminology may have been useful in the 1920s when physicists were grappling with fitting newly discovered wave behaviors into the existing particle physics framework, but they may have become an obstacle to understanding what quantum physics is trying to tell us about the intrinsic nature of matter.

The support for part (ii) is an account of what measurement physically is. Energy waves have extended dynamical structures that evolve over time, exhibit wave interference and entanglement effects, and carry no precise values of any kind. Precise values appear only when a measurement device absorbs a quantum of energy and produces an energy signature the device translates into the variables used in physics equations, stores the variable values in device memory, and presents them on computer screens. In short, the WEX principle asserts that particles as they are conventionally envisioned are illusions while energy waves are the sole ontological primitive. Embracing this view requires replacing the particle terminology of quantum physics with terminology that recognizes the intrinsic wave nature of matter. Thirteen precise definitions are offered to remove ambiguities and allow the principle to naturally address a series of quantum mysteries throughout the paper.

The WEX principle is not a new theory as it adds no mathematics, inherits the Born rule and Standard Model, shares every empirical prediction of existing quantum theory, and makes no new predictions at this time. It is offered as a principle in the sense of a constraint on what any adequate account of quantum phenomena must take to exist and persist, not as a mechanism that selects individual outcomes. Its value lies in its ability to account for aspects of the measurement problem, Bell correlations, weak measurement, double slit and delayed choice experiments, and observer paradoxes while requiring nothing beyond our physical universe

Keywords: wave realism; spatiotemporal realism; wave packet; quantum interpretations

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1. Introduction

The ‘particle view’ of matter was first proposed by Greek philosopher Democritus around 400 BCE and persisted for millennia until quantum theory uncovered a wave aspect of matter. [1,2] The ‘wave-particle duality’ view quickly replaced the particle view as this hybrid framing allowed for both wave and particle aspects of fundamental entities, depending on context.

The paper argues that quantum mysteries and paradoxes arise from mathematics, interpretations, and terminology that remain grounded in the assumption that particles are fundamental constituents of reality while attributing little-to-no ontological status to the wave aspect of matter. Physicists speak of particles in superposition existing in multiple places simultaneously in an abstract higher-dimensional mathematical space, rather than considering the possibility the quantum formalisms are describing physically real wave energy patterns in our physical universe. Elementary particles are viewed as possessing hidden properties when they are not being measured, whereas the wave energy patterns described by quantum formalisms have spatial extent that span many points in space and have dynamical properties that evolve over time. Wave functions are viewed as collapsing from many possible particles in superposition to one actual particle upon measurement, instead of viewing measurement as an extended wave energy

pattern that exchanges energy with a measurement device at a specific point in space and time. Entangled particles influence each other at a distance, yet wave functions of entangled pairs describe only a single inseparable wave-like entity. These particle-centric perspectives and terminology were useful in the 1920s as physicists grappled with fitting the newly discovered wave behaviors into their existing particle physics framework, but they have since become an obstacle to understanding what quantum physics is telling us about the intrinsic nature of matter.

The wave-particle duality view was developed to integrate the particle and wave aspects of matter into a coherent physics framework. But in practice quantum terminology has remained overly committed to the particle aspect while treating the wave aspect as an experimental artifact that must be addressed but is not generally viewed as having equal ontological status as particles. Since the particle view and the wave-particle view have been unable to resolve the mysteries and paradoxes that pervade quantum theory, this paper asks which ontology best addresses these mysteries and arrives at a third possibility, that the intrinsic nature of matter is not particle-like, not wave-particle-like, but purely wave-like. The paper is not offering a wave function realism view, but a wave realism view. Wave function realism has been extensively explored in higher dimensional spaces and in the many-worlds interpretation. The present claim is that physically real energy waves are the sole ontological primitives existing in the space and time dimensions of our physical universe, not in an abstract higher dimensional mathematical space. The claim is stated as a two-part principle, one part on what exists and persists while the other part states what this implies for particles, and the paragraphs below build the support for each.

The paper starts from a spatiotemporal realism constraint that requires fundamental entities to physically exist in the universe we can observe, the space and time where physicists and measurement devices exist. All evidence in physics is gathered there so any ontology that places its fundamental entities elsewhere must explain how they connect to the instruments that detect them. This constraint does not claim that nothing lies in higher dimensions nor beneath spacetime but simply requires fundamental entities to physically exist in our observable universe. This constraint is shared by the primitive ontology approach to quantum theory which locates what exists in space or spacetime and treats the wave function as a law or model. [3,4,5,6]

The spatiotemporal constraint is also the path by which the paper's argument was reached. The abstract mathematics of quantum formalisms are often read as implying that no physical reality exists independent of observation or cannot be known, as in some readings of the Copenhagen interpretation. Strict realism takes the opposite course. If the mathematics seems to require entities outside of space and time, that mathematics is treated as a modeling tool and the question becomes what the formalisms say about entities inside space and time.

Eleven quantum formalisms are compared (§2) which predict the same measurement outcomes using radically different assumptions for their mathematical constructions and the central objects they treat as fundamental. Since all eleven formalisms rely on higher-dimensional mathematical spaces to make predictions for the outcomes of quantum experiments, taking any given formalism as literally describing fundamental entities requires dimensions beyond the space and time dimensions of our physical universe to literally exist. The alternative is to view the formalisms as models that predict outcomes, not as literal descriptions of fundamental entities as they exist in space and time, which is the perspective taken by the paper.

Under the paper's spatiotemporal constraint, what the formalisms share is a more reliable guide to what can be inferred about the ontology of fundamental entities as they exist in the physical

universe. The shared features are discussed in §2 and describe fundamental entities which have extended structures that dynamically evolve, can interfere and entangle with one another, contain energy that is correlated to frequency and exchanged in discrete quanta when measured, exhibit non-local correlations, and produce definite values only when measured in the space and time where physicists and devices exist. The paper argues these properties and behaviors describe physically real energy waves that persist over time while the particle aspects only appear momentarily when a measurement device absorbs energy from a fundamental entity at a specific point in space and time. Wave realism is therefore the conclusion of the analysis under a spatiotemporal realism constraint as opposed to an additional ontological assumption. Part (i) of the WEX Principle states that conclusion, and part (ii) states what follows for particles.

> ***The Wave Energy Exchange (WEX) Principle:*** *(i) The sole persistent constituents of physical reality are spatially extended energy waves that can exchange energy with other waves, interfere and/or unify with them, and dynamically evolve in our space and time universe. (ii) Particles with precise property values are point-in-time signatures of quanta of energy emitted by an energy wave and absorbed by a measurement device.*

Part (i) leaves open what a measurement outcome is. Part (ii) answers that a particle with precise property values is the record of a quantum of energy emitted by an energy wave and absorbed by a measurement device. That answer depends on what a measurement is, and quantum physics lacks precise definitions for many important terms used in the field. For instance, there is no definition for what constitutes a measurement nor a measurement device, which leads directly to the ambiguities surrounding the measurement problem, the central mystery of quantum physics. There is no guidance nor set of rules to define the proper scope for modeling quantum systems with wave functions or other central mathematical objects, creating ambiguity for locating Heisenberg cuts for any given quantum system which leads directly to paradoxes such as Schrödinger's Cat and Wigner's Friend. The paper aims to resolve these ambiguities and confusion by stripping away ill-defined particle-centric terms and replacing them with thirteen precisely defined wave-centric terms related to measurement, measurement devices, measurement outcomes, rules that limit model scope, entanglement, energy exchange, and energy dynamics (§3).

Status of WEX. The paper offers no new mathematics but is instead an ontological reading of the common features across formalisms and the evidence gathered over a century of quantum experiments from a spatiotemporal realism perspective. It is stated as a two-part principle and includes a series of precise definitions grounded in spatiotemporal realism terminology. It is not a new physical theory as it adds no mathematics, inherits the Born rule and Standard Model, and makes the same empirical predictions as standard quantum theory. The paper does not at this time include any unique predictions that could distinguish the WEX ontology from the alternatives but may in the future do so. The case for WEX therefore rests on its explanatory value, the constraints imposed on it by its precise definitions, and its ability to resolve mysteries and paradoxes.

Why a principle. The WEX Principle is a principle in the sense of a principle theory, which states a general constraint that any adequate account of a domain must satisfy without supplying the mechanism for every detail. [7] It is not a principle in the sense of an empirical law or an axiom. The two parts have different support. Part (i) is an inference from the eight shared features (§2), and part (ii) rests on the definitions of measurement, measurement device and particle signature (§3). Three features support WEX as a principle. First, it is formalism-agnostic. It applies to the eight features that all eleven formalisms share and does not depend on the mathematics of any one of them (§2). Second, it does derivational work. Definite measurement outcomes, entanglement as

unification, the reading of weak measurement, and the relocation of non-locality to the interior of a single wave all follow from the principle together with the definitions and the inherited Born rule and Standard Model (§4 to §8). Third, it deliberately omits the dynamics that select where each energy exchange occurs (§4.2), which is what distinguishes a principle from a constructive theory. The support for part (i) is an inference to the best explanation from the shared features and not a derivation. It does not establish that no other ontology is possible, so it claims to be a well-supported statement of what exists and persists but not the only possible one.

WEX exists alongside other primitive ontologies, not apart from them. Pilot wave theory takes particles as the primitive ontology, spontaneous collapse models take a matter density or flashes and modify the dynamics to select outcomes, and spacetime state realism takes the quantum state to be localized in spacetime regions [4,5,8]. The WEX shared features approach is consistent with persistent energy waves as fundamental while granting particles no ontological status, viewing them instead as evidence of an energy exchange event that occurred at a specific point in space and time. WEX is unique among the alternatives in that it requires no additional dynamics, requires no collapse postulate, and requires no structure beyond the singular physical universe that we find ourselves living within. Pilot wave, spontaneous collapse, spacetime state realism and every interpretation of quantum physics are constructed upon formalisms that include higher-dimensional mathematical spaces. Therefore, any quantum interpretation that takes any formalism as literally describing fundamental entities requires additional dimensions to physically exist. Wave function realism, including the form commonly paired with many-worlds, instead takes the wave function itself as physically real in a higher-dimensional space. The transactional interpretation shares WEX's two-sided view of energy exchange while its relativistic version places the possibilities it posits in a pre-spacetime substratum that WEX does not require. That said, WEX does not rule out the existence of higher dimensions nor structure beneath spacetime, it simply does not require either (§4.2, §13).

WEX is also open to evidence that would count against it. Its scale-independence claim (§10) would be undermined by a demonstrated size-dependent limit on wave interference effects that could not be traced to energy exchange. For example, spontaneous collapse and gravity-induced collapse models (§4.2) predict a size-dependent breakdown of interference while WEX, like standard quantum theory, predicts none, thus a positive result for those models would count against WEX. And because WEX takes formalism shared features as its foundation, a formalism or geometry describing fundamental entities that reproduces the results of quantum physics without representing or predicting those features would count against WEX (§13).

The WEX principle and its precise definitions together address longstanding mysteries and paradoxes that remain unresolved under the current wave-particle duality paradigm. Standard quantum theory often refers to the extended energy patterns described by the formalisms as wave packets, so this term will be used throughout the paper to refer to the fundamental entities described by the WEX principle. The bulk of the paper traces the principle's consequences, yielding the following:

- Localization is grounded in quantized energy exchange, a physical mechanism integrating the Standard Model with the formalisms, thus no ad hoc collapse postulate is needed. Measurement outcomes are definite and localized because a quantum is exchanged whole at a position in space and time. (§4)

- Entanglement becomes unification, a merging of physically real wave patterns that combine their energy structures to form a single unified energy wave with the aggregate energy structure of the merged waves. Nothing is correlated in this view because there is only one entity and it carries no definite values to correlate. (§5)
- Bell's theorem assumes entangled systems are separable and carry pre-existing values that can be correlated. Bell's premises do not apply to WEX fundamental entities because a unified wave packet is a single non-separable object that carries no pre-existing values to correlate, consistent with the non-separable nature of the central objects of all formalism descriptions of entangled systems evolving as single unified objects. Conservation laws acting on a single extended structure give a physical account of the complementarity underlying EPR correlations. WEX does not restore local causality in the sense that Bell's theorem rules out but constrains non-locality to the redistribution of energy within a single extended wave packet, a dynamic that every wave packet shares. (§6)
- Weak measurement defines no value during the weak interaction because the coupling does not produce an independent energy exchange, accounting for the system's minimal disturbance and offering a straightforward reading of anomalous weak values. (§7)
- Delayed choice experiments require no retro-causality because no which-path value exists before an energy exchange defines one, and wave packets always go through both slits. Double-slit, delayed-choice, entangled-pair, and Bose-Einstein condensate experiments share one physical description: a single extended wave packet undergoes a localized energy exchange that constrains the remainder through conservation laws. (§8)
- Energy exchange alters the physical structure of the wave packets involved, requiring wave function reconstruction after each exchange to accurately model the updated state of the system. The wave function collapses in its usefulness, as does every mathematical model of a system once that system exchanges energy with another. Observer paradoxes are resolved by removing observers and other objects not involved in the next energy exchange that triggers wave function reconstruction. (§9)
- There is no boundary between the quantum and classical worlds where quantum dynamics cease to exist. Wave packet energy exchange dynamics apply at all scales of the universe from organic molecules, to living organisms, to the plasma that forms stars and the solar wind, to the dynamics of event horizons surrounding black holes. (§10)
- Quantum Information Theory (QIT) becomes the study of how wave packet structure constrains energy exchange, determining which measurement outcomes are possible. What changes is the context, not the experimental results. QIT is the study of information production, not information discovery. (§11)
- Quantum computing exploits two complementary resources: wave packet geometry (hardware) contains a continuum of structural degrees of freedom, and quantum algorithms (software) manipulate this geometry through controlled unifying energy exchange. The result is a geometrically optimized answer defined at measurement, which WEX reads as a form of geometric computing. (§12)
- WEX is scale-independent, formalism-agnostic, and geometry-independent. It applies equally to non-relativistic and relativistic systems, in Euclidean or curved geometries,

across any number of dimensions, and is independent of mathematical frameworks describing wave packet dynamics. These follow from the ontology itself. If wave packets are the sole persistent constituents of physical reality, then they are the basis of matter at every scale, and any formalism or geometry describing fundamental entities is either consistent with WEX or counts against it. (§13)

2. Common Features of Eleven Quantum Formalisms

The paper's analysis begins by comparing the mathematical structure of eleven frequently used quantum formalisms.

Table 1. Mathematical Constructions of Leading Quantum Formalisms

Formalism	Central Object	Measurement Problem Response	Required Dimensions (N = # of Particles)	Relativistic	Relation to Wave Mechanics
Wave Mechanics [1]	Wave Function	Collapse Postulate	3N plus Time	With Modification	Reference formalism
Matrix Mechanics [9]	Observable Matrices	Collapse Postulate	Infinite Dimensional Matrices	Adapts Naturally	Equivalent reformulation
Phase-Space [10,11]	Quasi-Probability Distribution	Collapse Postulate	6N plus Time	With Modification	Equivalent reformulation
Density-Matrix [12]	Density Matrix	Collapse Postulate	Operators on Infinite Dimensional Space	Adapts Naturally	Equivalent, extended to mixed states
Second Quantization [13]	Occupation Number of Field Modes	Collapse Postulate	Infinite Dimensional Space of Occupation Numbers	Adapts Naturally	Equivalent, extended to variable particle number
Path Integral [14]	Sum over Histories	Not Addressed	Infinite Dimensional Space of Paths Through 4D Spacetime	Adapts Naturally	Equivalent reformulation
Action Principle [15]	Quantum Action Principle	Collapse Postulate	Fields over 4D Spacetime in Infinite Dimensional Space	Adapts Naturally	Equivalent reformulation
Algebraic QFT [16]	Algebras of Local Observables	Not Addressed	Regions of 4D Spacetime with Infinite Dimensional Representations	By Construction	Different structure, same predictions where domains overlap
Hamilton–Jacobi [17]	A Complex Action	Collapse Postulate	3N plus Time	With Modification	Equivalent reformulation
Pilot Wave [18]	Wave Function plus Hidden Particles	Definite Positions Assumed	3N plus Time	With Modification	Wave mechanics plus particle positions
Direct-Action [19,20,21]	Direct Interactions Between Charges	Energy Absorption	4D Spacetime plus Infinite Dimensional State Space	By Construction	Different structure, same predictions where domains overlap

Wave mechanics became the standard framework in the 1920s for practical reasons. Its differential equations used mathematics that physicists were already familiar with from modeling the wave behavior of sound, light, and vibrating structures. It made models of the hydrogen atom far easier to solve than matrix mechanics (its main competitor in the 1920s) and its wave concepts were much easier to visualize than abstract matrices. Wave mechanics has remained the dominant formalism ever since, which is why the last column in the table compares all other formalisms to it. The column shows that 9 of the 11 formalisms are reformulations or extensions of wave mechanics, leaving Algebraic QFT and Direct-Action theory as the only fundamentally different approaches.

While wave mechanics remains the dominant formalism, other formalisms are routinely used for applications where their unique mathematical structures simplify certain types of calculations. Matrix methods are preferred for quantum circuits, second quantization for many-particle systems, path integrals for particle collisions, and phase-space methods for quantum optics. Since all formalisms yield the same predictions where their domains overlap, physicists can use them as interchangeable models of the behavior of quantum systems, with the nature of the problem at hand driving the choice of formalism used to model any given system.

Some formalisms are relativistic by construction, some adapt naturally, and others require modifying or replacing their core equation. The 4D spacetime manifold of relativity theory is the conventional mathematical model used to describe the physical universe, a model that WEX accepts as a mathematical tool but not as an ontologically real object. The universe itself is physically real in WEX, not the spacetime model that mathematically describes it. WEX treats no mathematical object used in a formalism as a fundamental physical entity and views them as models that predict the behavior of physically real objects that exist in our universe.

Relativistic quantum field theory (QFT), including the Standard Model, is not a separate formalism but is expressed through second quantization, path integral, and algebraic formulations. QFT is commonly read as treating elementary particles as excitations of underlying quantum fields, implying that quantum fields are more fundamental than particles. WEX treats quantum fields as part of QFT's abstract mathematical model that requires infinite mathematical dimensions to model a quantum system's degrees of freedom. Neither WEX nor the mathematics of QFT requires treating quantum fields as physically real substances. Quantum direct-action electrodynamics shows that electromagnetic fields can be removed from the mathematics altogether without changing its predictions for the scattering processes analyzed, provided all emitted energy is eventually absorbed. [20] The concept of quantum fields is a useful mathematical tool for modeling purposes but need not be ontologically real and is not a shared feature across formalisms. Under WEX, wave packets (defined in §3.1), not fields, are the sole fundamental physical entities that QFT describes. This is consistent with WEX's treatment of wave packets as spatially extended, since the sharpest objections to the particle ontology of QFT concern strictly localized, point-like particles.

Each formalism relies on add-on frameworks to handle different kinds of problems such as perturbation theory for systems too complex to solve exactly, the Pauli equation for spin, and the Dirac equation for relativistic particles. Each formalism also requires additional mathematical adjustments to ensure it produces accurate predictions, such as boundary conditions, absorber conditions, normalization, renormalization, ordering rules, regularization, gauge fixing, and/or rotation to imaginary time.

Seven formalisms do not address the measurement problem directly but instead utilize an ad hoc collapse postulate from outside the mathematics as a proxy for localization physics. Two do not address it at all while direct-action theory as further developed in the transactional framework [21] addresses localization with physics attributing it to energy absorption, a view that is consistent with WEX. Pilot wave theory evades the measurement problem by constructing the formalism from the start around the assumption that particles always have definite positions, thus its wave function never needs to collapse.

The formalisms have radically different mathematical objects at their core: wave functions, observable matrices, quasi-probability distributions, density matrices, occupation numbers of field

modes, histories, action principles, a complex action, algebras of local observables, a wave function guiding hidden particles, and direct interactions between charges without an associated field. The formalisms all rely on higher-dimensional mathematical spaces to model the properties and behaviors of their core mathematical objects and to predict the range of possible outcomes of measurements of quantum systems.

Given that all eleven formalisms predict the same results within their domains despite having vastly different mathematical frameworks, the paper treats them all as valid predictive models and refers to them collectively as 'formalisms.' The significant diversity in core mathematical objects, add-on frameworks, procedural adjustments, and the reliance of the formalisms on abstract mathematical spaces with many more dimensions than what appears to exist in our physical universe suggests that no single formalism should be taken literally as an accurate depiction of quantum scale entities as they truly exist in our physical reality. Extrapolating the mathematics of any single formalism to make ontological claims about the intrinsic nature of reality yields vastly different ontologies based on the formalism chosen, many of which are incompatible with one another. The paper argues that this approach confuses a mathematical model of the behavior of an object with the object as it exists in physical reality.

Consider a Newtonian physics model that accurately predicts the dynamics of a car rounding a corner at high speed. The car is modeled as a point mass in Euclidean space with position, velocity, and acceleration vectors. Gravity, wind resistance, and the friction between the road and tires can be accounted for with additional force vectors. The radius of the turn fixes the inward acceleration that this friction must supply. These vectors are abstract mathematical representations of the properties of the car and the environment it interacts with, and collectively they accurately describe the dynamics of the car as it rounds the turn, but do not describe the car as it exists in physical reality. A model built in a space with a separate dimension for every possible position of every part of the car would predict the same dynamics, yet no one would conclude that the car lives in that space. Likewise, while the modeling of vectors in abstract mathematical space accurately predicts the behavior of quantum scale entities, they do not describe the quantum scale entities as they exist in physical reality. WEX rejects the inference from a model's predictive accuracy to the claim that its mathematical objects describe the intrinsic nature of quantum scale entities as they exist in our physical reality.

The paper argues that ontological claims about the intrinsic nature of quantum reality should be grounded in the common set of attributes that all formalisms share. Where mathematically equivalent representations of quantum theory diverge on what they say about fundamental entities, only the attributes that stay fixed across them are treated as a defensible guide to what quantum theory says about the intrinsic nature of physical reality. Agreement across formalisms is not treated as a vote, but rather what is invariant across formalisms is treated as a guide to what exists as a structural-realist inference that constrains any ontological reading of quantum physics. Nine of the eleven formalisms can be viewed as reformulations or extensions of wave mechanics thus their agreement is to be expected, so claiming that eleven formalisms agree may overclaim the point. Nevertheless, the invariance argument remains unchanged if viewed across just the three structurally unique formalism types: Algebraic QFT, Direct-Action theory, and the nine wave mechanics formalisms grouped together as a single type. However, the fact that the nine variations of wave mechanics make the same predictions despite widely divergent central objects is worth noting as an additional argument against making ontological claims based on any given formalism's mathematical structure. While this invariance argument does not establish by itself

that the views expressed in the paper are necessarily correct or the only viable candidate, it does argue that any ontological claims regarding quantum scale entities should be constrained by the shared features across equivalent formalisms.

Table 2 identifies the properties and behaviors of fundamental entities as expressed by each formalism. Common features across quantum and classical physics such as thermodynamic laws and conservation laws are omitted because the attributes were chosen to contrast quantum entities with classical particles. Eight properties and behaviors are either directly represented or predicted by every formalism:

1. **Variable spatial extension.** Fundamental entities are spread out over a region of space between measurements, and the extent is not fixed by species.
2. **Continuous structural evolution.** The spatial extension and internal energy structure of fundamental entities change continuously over time between measurements. Energy exchanges are events within this evolution, not interruptions of it.
3. **Energy–frequency correlation**. The energy contained in a fundamental entity is proportional to its frequency via Planck's constant, $E = hf$.
4. **Interference patterns.** Overlapping fundamental entities can constructively and destructively combine the amplitudes of their energy patterns.
5. **Non-separable entangled systems.** Overlapping fundamental entities can combine their energies to form a single non-separable entity that can no longer be treated as two independent entities.
6. **Discrete energy exchange.** Energy is only exchanged in discrete quanta when measured.
7. **Values Defined in Space & Time at Measurement.** Defined values of the properties of fundamental entities only appear when a measurement occurs in space and time.
8. **Non-local correlations.** Measurement outcomes of unified fundamental entities performed at separated locations can be correlated in ways that appear to violate the speed of light limit set by special relativity.

Table 2. Attributes of Fundamental Entities Across Formalisms

Formalism	What Constitutes the Entity	Variable Spatial Extension	Continuous Structural Evolution	Discrete Energy Exchange	Energy–Frequency Correlation	Interference Patterns	Non-Separable Entangled Systems	Non-Local Correlations	Values Defined in Space & Time at Measurement	Values Defined in Space & Time Pre-Measurement
Wave Mechanics	Not specified	Represented	Represented	Predicted	Represented	Represented	Represented	Predicted	Predicted	No, Only in Abstract Mathematical Space
Matrix Mechanics	Not specified	Predicted	Represented	Represented	Represented	Predicted	Represented	Predicted	Predicted	No, Only in Abstract Mathematical Space
Phase-Space	Not specified	Represented	Represented	Predicted	Predicted	Represented	Represented	Predicted	Predicted	None
Density-Matrix	Not specified	Represented	Represented	Predicted	Represented	Represented	Represented	Predicted	Predicted	No, Only in Abstract Mathematical Space
Second Quantization	Not specified	Represented	Represented	Represented	Represented	Represented	Represented	Predicted	Predicted	No, Only in Abstract Mathematical Space
Path Integral	Not specified	Represented	Represented	Predicted	Predicted	Represented	Predicted	Predicted	Predicted	None
Action Principle	Not specified	Represented	Represented	Predicted	Predicted	Represented	Predicted	Predicted	Predicted	No, Only in Abstract Mathematical Space
Algebraic QFT	Not specified	Indirectly Represented	Represented	Predicted	Predicted	Predicted	Represented	Predicted	Predicted	No, Only in Abstract Mathematical Space
Hamilton–Jacobi	Not specified	Represented	Represented	Predicted	Represented	Indirectly Represented	Indirectly Represented	Predicted	Predicted	None
Pilot Wave	Particles with positions, guided by wave function	Represented	Represented	Predicted	Represented	Represented	Represented	Represented	Predicted	Assumed for Position. Other Properties Only in Abstract Mathematical Space
Direct-Action	Charged particles interacting directly	Predicted	Predicted	Represented	Predicted	Predicted	Predicted	Predicted	Predicted	No, Only in Abstract Mathematical Space
Classical Particle (reference)	*Particles*	*No (Fixed Extension)*	*No (Only Trajectory)*	*No (Continuous)*	*No*	*No*	*No*	*No*	*Yes (Always Defined)*	*Yes (Always Defined)*

Represented: The attribute appears in the formalism's central mathematical object.

Predicted: The attribute appears in the formalism's results but not in its central object.

Indirectly Represented: The attribute appears in the formalism's mathematical structure only after applying additional constructions that are routinely used with it.

Values at measurement: In the "Values Defined in Space & Time at Measurement" column, Predicted means that the formalism's outcome rule (the Born rule, together with a collapse postulate where one is used) assigns defined values in space and time only at measurement. No formalism derives the occurrence of a single outcome from its central object (§4.1).

Multi-entity systems: For systems of more than one entity, the central objects are defined over higher-dimensional spaces. Under the spatiotemporal constraint (§1), each attribute is scored by how it appears in the three dimensions of space and time, where spatial extension is obtained from the central object by constructions that are routinely applied.

Selection criterion: Attributes were chosen to contrast quantum entities with classical particles. Features that classical particles share, such as conservation laws and no-signaling, are omitted. The Classical Particle row is included for reference purposes only, not as a formalism.

Uncertainty relations and contextuality follow from the absence of defined values before measurement and are not tabulated separately.

The entity column sits next to the formalism column to show that the formalisms are silent on, or disagree about, what is fundamental, so only the attributes that stay fixed across formalisms are read for invariance.

The paper reads the common features as describing the fundamental entities as physically real energy waves that persist in our space and time universe while particles only appear briefly during measurement, suggesting particles should not have ontological status but instead are emergent phenomena manifesting during energy exchange. The first five features clearly illustrate the advantages of this wave realism perspective.

1. **Variable spatial extension.** While particles can certainly have spatial extension, the Standard Model of Elementary Particles treats fundamental entities as point objects that have no spatial extension. Meanwhile all formalisms describe fundamental entities that are spread out over a region of space. That their spatial extent cannot be precisely quantified does not mean that they have none. Spatial extent is consistent with the physically real, spatially extended wave energy patterns advocated in WEX, but not consistent with the dimensionless particles described by the Standard Model and assumed in many quantum formalisms and interpretations. For fundamental entities to exist in our physical universe they must have extension in the three spatial dimensions that we experience.
2. **Continuous structural evolution.** Fundamental entities dynamically evolving their spatial extension over time is consistent with WEX physically real, spatially extended wave energy patterns, meanwhile dimensionless particles lack any spatial extent that can evolve.
3. **Energy–frequency correlation**. That the energy of fundamental entities is proportional to its frequency points directly to the intrinsic wave nature of matter. Meanwhile, dimensionless particles have no three-dimensional physical structure that can vibrate at a frequency.
4. **Interference patterns.** Fundamental entities constructively and destructively combining their energy patterns point directly to the intrinsic wave nature of matter because waves interfere with one another at all scales of physics. It is difficult to envision how a single dimensionless particle can interfere with itself in a double slit experiment to produce an interference pattern in our three-dimensional physical universe.
5. **Non-separable entangled systems.** Fundamental entities combining their energies to form a single non-separable entity is consistent with both quantum and classical theories of electromagnetism where electromagnetically active matter at any scale can seamlessly combine its energy to form higher power electromagnetically active matter as evidenced by a radio station transmitter, a lightning strike, or the plasma that forms stars. Meanwhile it is difficult to envision how dimensionless particles can seamlessly combine to form three-dimensional matter structures in our physical universe.

While the next two common features can be viewed from either a wave or particle perspective, neither is a feature that persists over time thus should not be read as ontological primitives. Both features relate to energy exchange events that always occur at a specific point in space and time.

6. **Discrete energy exchange.** Energy is always exchanged in discrete quanta when measured. These energy exchange events form the basis of the Standard Model which WEX reads as evidence of an energy exchange between a fundamental entity and a measurement device, not as evidence of a physically real particle that existed prior to the energy exchange.
7. **Values Defined in Space & Time at Measurement.** The formalisms all assign definite property values in the space and time of our physical universe only at measurement. Before or after measurement the formalisms ascribe no precise values to fundamental entities in

space and time, only in the abstract higher-dimensional mathematical spaces the formalisms utilize to make predictions.

The particles of the Standard Model were defined by analyzing the energy absorbed by measurement devices. Because a quantum of energy absorbed by a measurement device always occurs at a specific point in space, standard quantum theory reads this as particles having no dimensions, or at most having dimensions no greater than the Planck length. These two common features across formalisms directly account for the elementary particles in the Standard Model.

WEX reads these two common features and the Standard Model entities they define differently than standard quantum physics. WEX views the particles in the Standard Model not as fundamental entities that exist and persist in our physical reality, but as types of possible energy exchanges that fundamental wave energy patterns can engage in. Since all properties of elementary particles are defined during measurements which last for a few femtoseconds, WEX views the appearance of a particle as evidence of energy exchange, the energy signature of a wave energy exchange event.

While one could argue that pilot wave theory assigns definite positions in spacetime prior to measurement, these positions cannot be known prior to measurement as they are hidden from view and ultimately defined in space and time by the higher-dimensional guiding wave function that exists in abstract mathematical space. Furthermore, pilot wave theory was constructed with the starting assumption that particles have precise positions at all times, an ontological assumption baked into the theory by design. Note that the Hamilton-Jacobi formulation uses closely related mathematics to pilot wave theory without assuming particles have definite position pre-measurement, thus the particle position assumption in pilot wave theory can be viewed as an additional assumption added by design and not required by its mathematics.

8. **Non-local correlations.** The last common feature is the non-local correlations that lie at the core of the EPR paradox. Under both the standard and WEX readings of quantum physics, these correlations provide strong evidence of some form of non-local influence operating at the quantum scale. WEX does not claim to explain non-local correlations but limits them to the internal energy dynamics of a single unified wave packet (§6.4).

Table 2 also contains two attributes that the formalisms do not agree on: what constitutes a fundamental entity and whether defined values exist pre-measurement. Nine formalisms decline to identify any fundamental entities while the two that do so define them as a starting assumption of the formalism. The WEX principle identifies the physically real wave energy patterns inferred from a spatiotemporal realism reading of shared formalism features as the sole fundamental constituents of physical reality.

Ten formalisms assign no definite position prior to measurement in our physical universe, with pilot wave theory the sole exception. As mentioned earlier, this theory was constructed with particle positions as a starting assumption and built its framework around that assumption. Yet it requires a wave function in a high-dimensional configuration space to guide the particles and to define precise particle positions along with other defined properties at measurement.

Every quantum formalism was constructed as a mathematical model of fundamental entities designed to predict what physicists can measure in the space and time dimensions of our physical universe. In each case, higher-dimensional mathematical spaces model the degrees of freedom of the properties of quantum scale entities which have definite values in our physical universe only when a measurement occurs.

The shared features are what every formalism must reproduce with its perferred mathematics, so the paper takes them to reflect the core attributes of fundamental entities, while the differing mathematics reflects modeling choices. The attributes that survive every change of model provide a better foundation for ontological claims than the mathematics of any one model. The paper reads these eight core attributes as describing fundamental entities that are not particle-like, not wave-particle-like, but purely wave-like. Under the paper's spatiotemporal constraint, the only fundamental entities that appear to exist are physically real wave energy patterns that are captured in a two-part claim:

> ***The Wave Energy Exchange (WEX) Principle:*** *(i) The sole persistent constituents of physical reality are spatially extended energy waves that can exchange energy with other waves, interfere and/or unify with them, and dynamically evolve in our space and time universe. (ii) Particles with precise property values are point-in-time signatures of quanta of energy emitted by an energy wave and absorbed by a measurement device.*

While the WEX principle was reached by an invariance argument and a firm commitment to the concrete physical reality of the universe each of us experiences, WEX can also be viewed as a wave realism ontology for quantum physics. Table 3 compares WEX wave realism with the major quantum interpretations on the questions that separate them [4,5,8].

Table 3. WEX Compared with Major Interpretations

Interpretation	What is Fundamental in Our Physical Universe?	What Lies Beyond Our Physical Universe?	What is Added to Produce Measurement Outcomes?	Where Does Non-Locality Physically Exist?
WEX Wave Realism	Wave packets	Nothing required	Nothing (Born rule inherited)	Energy redistribution within a single wave packet
Wave-Function Realism	Nothing as 3D space is considered emergent	Wave function field in configuration space	Varies by version (none, collapse, or guidance)	Wave function field in abstract configuration space
Many Worlds	Nothing (our branch emerges)	Universal wave function and other branches	Nothing (all outcomes occur)	Disputed (non-separable state, branching claimed local)
Spontaneous Collapse	Matter density or flashes	Wave function (law-like or a field, by version)	Dynamical collapse term	Collapse dynamics
Pilot Wave	Particles	Guiding wave function (law-like or a field, by version)	Guidance equation	Guidance equation
Copenhagen	Measurement outcomes	Not asserted	Collapse postulate	Not addressed
QBism	Agents and their experiences	Not asserted	Nothing (the state is a belief, and the update replaces collapse)	None (correlations reflect an agent's expectations)
Consciousness-Causes-Collapse	Conscious observers	Mind (in dualist versions)	Collapse triggered by consciousness	Instantaneous collapse (rarely addressed)
Relational	Systems and their relations	Not asserted	Relative facts (no absolute outcomes)	Argued absent (outcomes are relative to the observing system)
Transactional	Waves in spacetime or actualized transactions	Varies (pre-spacetime in the relativistic version)	Backward-in-time influence	Time-symmetric exchange between emitter and absorber

The table entries describe each approach as commonly formulated, and less common versions differ. 'Our physical universe' is limited to the space and time in which physicists and their instruments exist (§1). 'Beyond our physical universe' covers abstract mathematical spaces, other world branches, plus any hypothetical dimensions and/or pre-spacetime structure.

The interpretations in Table 3 fall into five groups, and WEX differs from each in a different way. The first group, which includes Copenhagen, QBism, and relational quantum mechanics, declines to say what exists or makes facts relative to an agent or system. WEX takes a firm position on what exists and places it within our universe, independent of any observer. The second group, wave-function realism and many-worlds, takes the wave function as physically real in a space that

lies beyond the physical universe we live in. WEX treats the wave function as a mathematical model of wave packets that exist inside our universe, so nothing lies beyond it and every measurement has one outcome. The third group, pilot-wave and spontaneous collapse theories, keeps everything inside our universe but adds a persistent particle, matter density, or flash ontology together with a guidance equation or collapse term that lies in abstract mathematical space to select outcomes. WEX has no persistent particles and adds nothing to cause outcomes. The fourth group, consciousness-based collapse, gives conscious observers a special causal role. Under WEX, any energy exchange between two quantum systems eliminates the need for any causal influences external to the quantum systems. The fifth group, transactional and retro-causal accounts, shares WEX's two-sided view of energy exchange but requires influences that run backward in time or via structure beneath spacetime. WEX requires neither.

Among the approaches compared in Table 3, WEX is the only ontological view that places everything inside our observable physical universe, requires nothing beyond it to produce outcomes at the price of leaving the location of each exchange to the Born rule (§4), and constrains non-locality to the internal energy dynamics within a single wave packet such that no independent quantum scale entities exhibit correlations that violate special relativity (§6). The nearest neighbors are the primitive ontology versions of pilot-wave and spontaneous collapse theories, which place a real physical entity inside our universe but add a guidance equation or dynamical collapse term, both reliant on wave functions in abstract mathematical space.

3. The Wave Energy Exchange (WEX) Principle and Definitions

The WEX Principle is a two-part claim that elevates the ontological status of the wave nature of matter while denying any ontological status to particles:

> ***The Wave Energy Exchange (WEX) Principle:*** *(i) The sole persistent constituents of physical reality are spatially extended energy waves that can exchange energy with other waves, interfere and/or unify with them, and dynamically evolve in our space and time universe. (ii) Particles with precise property values are point-in-time signatures of quanta of energy emitted by an energy wave and absorbed by a measurement device.*

Thirteen precise definitions are provided below which attempt to remove all ambiguities and unlock the power of the WEX principle to resolve quantum mysteries and paradoxes.

3.1 Wave Packets

The WEX principle is a claim about energy exchange, so it requires an account of what exchanges energy, which in standard quantum theory are called wave packets. Wave packets are not mathematical concepts nor a wave aspect of physically real particles. They are the only physically real entities that exist in nature.

> **Wave Packet.** A physically real pattern of energy that oscillates as it propagates through the physical universe, can interfere and/or unify (i.e. entangle) with other wave packets when overlapping, exchanges energy with other physically real entities, and exists independent of measurement or observation. A wave packet has 'structural features' that include fixed identity features that define its species in the Standard Model and dynamical features that change and evolve over time. A wave packet's structural features determine its energy exchange possibilities.

Identity Features. Intrinsic properties that define a wave packet's species in the Standard Model, including mass (i.e., rest energy), charge, and intrinsic angular momentum (i.e. spin quantum number). This category of structural features is identical for every wave packet of the same species and does not depend on measurement. Inherited from the Standard Model.

Dynamical Features. Structural properties that can vary within a wave packet, including spatial extent, geometry, momentum, axis of energy rotation, handedness, frequency, wavelength, relative phase, polarization, energy distribution, and degree of unification with other wave packets. Dynamical features constrain what outcome values measurement devices can read during an independent energy exchange.

In standard quantum theory, energy is treated as an observable, undefined until measurement, with systems permitted to exist in superpositions of energy eigenstates. Under WEX, a wave packet's energy pattern is what physically exists and it exists independent of measurement. This is no different from a radio tower emitting physically real electromagnetic energy that is absorbed by radio receivers and exists independent of whether any radio receiver is turned on. The energy a star emits likewise exists regardless of whether anyone observes it. WEX accepts energy as a physically real phenomenon at every scale of the universe that exists independent of observation.

A wave packet's dynamical features evolve over time and are altered by any form of energy exchange or coupling to a field. [22] What wave function evolution accurately tracks is the evolution of a wave packet's dynamical features in physical reality, not a superposition of observable state vectors in abstract Hilbert space. This is consistent with ordinary wave packet dynamics: a free wave packet's spatial extent evolves over time under the Schrödinger equation, a textbook result usually described as wave packet spreading. WEX takes this spreading, and structural changes generally, as evidence of a physically real, continuously evolving energy pattern, not the evolution of a probability distribution over a hypothetical future measurement outcome.

Not every mathematical feature of a wave function corresponds to a wave packet structural feature. For example, global phase has no observable consequence and reflects the abstract character of Hilbert space rather than a change in wave packet structure. Contrast that with the relative phase across a wave packet's extent, which is physically meaningful and constrains interference and energy exchange outcomes (§8). Section 3.2 defines structural evolution as energy redistribution.

Structural features are not a second kind of information. They are properties that describe the physical attributes of a wave packet as it exists in physical reality. We assign numbers to these properties (e.g., charge −e, spin quantum number ½) as tools for categorizing and analyzing wave packet structure, but wave packets carry properties, not numbers. Measurement outcome values (defined as classical information in §3.4) are different in kind: they describe attributes of an energy exchange defined at measurement, not a property the wave packet possessed before measurement.

Consider a coastline as an analogy: it has a shape, the shape is real, it consists of various materials and elevations that vary along its length, and it changes over time due to erosion, human and animal activity, and other environmental factors. These features are not information about the coastline; they are properties the coastline 'has' in physical reality. These features exist prior to any survey, and they constrain what any survey could find. The survey records measurement outcomes with definite values and units at specific points in space and time. Wave packets and coastlines are what physically exist, while the quantitative measurement outcomes for both are informational

snapshots taken at a point in space and time. The analogy has limits. A survey instrument absorbs light the coastline scatters rather than energy from the coastline itself, so it records the coastline's current state without altering it. A quantum measurement device absorbs a wave packet's energy, so the exchange both defines outcome values and alters the wave packet it measures.

Two scope notes on the definition of wave packets. First, extension and propagation are asserted as spatiotemporal. Wave packets are extended in and propagate through the physical reality we inhabit, and the arguments of Sections 6 and 8 depend on this. Second, this paper deliberately leaves open whether wave packet structure is limited to the four dimensions of space and time that we directly experience given recent research suggesting spacetime may be emergent rather than fundamental. [23,24] Whether wave packet structures are confined to 4 dimensions of space and time, extend into additional dimensions, and/or extend into a substratum beneath spacetime, does not affect the WEX principle or any of its consequences. Section 13 states this position positively rather than as a hedge when it argues the WEX principle is scale, formalism, and geometry independent.

3.2 Wave Packet Energy Dynamics

Several terms related to energy exchange require precise definitions.

Energy Exchange. Any physical interaction in which energy is transferred or shared between two systems. Energy exchange alters the dynamical features of both systems, requiring reconstruction of the pre-exchange models to reflect the updated features of the post exchange systems (§3.5). Two systems must have compatible structural and coupling properties in order to exchange energy. There are two types of energy exchange, independent and unifying, as defined below.

Independent Energy Exchange. A quantum of energy emitted by one system and fully absorbed by another system where the two systems retain their independence. In order to qualify as an independent energy exchange, both systems must maintain separate energy structures post exchange with no shared energy, no interference between them, and no joint state model required to predict the behavior of either system. This test is physical and does not depend on scale since a quantum that stays coherently shared within a larger system fails it. An independent energy exchange can only occur in the discrete amounts of energy defined by the Standard Model. Inherited from quantum theory.

Unifying Energy Exchange. A transfer of energy between two independent systems that results in a single unified system that shares the combined energy of both systems. System independence is lost during a unifying energy exchange, and no energy escapes the combined system. A unifying energy exchange can occur in any amount of energy. An exchange of less than a quantum is always unifying since a sub-quantum amount cannot be exchanged between independent systems. Exchanging a quantum of energy can be unifying when its energy remains coherently shared within a larger system, as in Bose-Einstein condensates (§10).

Unified Wave Packet. Two independent systems lose their independence during a unifying energy exchange, becoming a single non-separable unified wave packet. The combined energy is coherently shared across the unified wave packet’s extent, and its structural features no longer belong to the predecessor wave packets individually. No

energy is emitted during the formation of a unified wave packet, so unification itself defines no values. This is the WEX definition of entanglement.

Energy Redistribution. The movement of energy within a wave packet or within a system of wave packets. Energy redistribution defines the evolving energy structure of a wave packet over time. Energy can concentrate in some regions and deplete in others, dynamically changing the wave packet's geometry and coupling possibilities with other wave packets and measurement devices.

Wave packet energy dynamics are not additional commitments but logical consequences of WEX's core ontology: wave packets are physically real energy patterns with dynamic structures that evolve over time, are subject to conservation laws, and exchange energy. Standard quantum mechanics leaves wave packet internal energy redistribution undefined while WEX defines it as a natural feature of the dynamic energy structures of wave packets.

These distinctions are foundational to understanding the energy dynamics of wave packets under WEX, how measurement produces definite values (§4), how entanglement creates unified wave packets without defining values (§5), and how quantum information theory studies structural constraints rather than latent values (§11).

The structural and coupling properties of interacting wave packets determine the magnitude of energy exchanged, not only whether one can occur. In a two-dimensional electron gas subjected to a strong magnetic field, the structural and coupling properties of the electrons and the field allow current to be carried by quasiparticles with one-third the charge of an electron.[25] The structural and coupling properties of interacting wave packets therefore determine both whether a quantum of energy will be exchanged *and* the quantum of charge and energy exchanged, a point developed further in the discussion of condensed matter physics (§10).

3.3 Measurement

The lack of definitions for the terms related to wave packet localization leads directly to the ambiguity of the measurement problem and resulting paradoxes that surround it. WEX offers precise definitions for two undefined terms in standard quantum physics:

Measurement. A physical process where an independent energy exchange occurs between a wave packet and a measurement device. Measurement produces outcomes with defined values. Observation of a quantum system that does not involve direct physical interaction with the energy exchanged does not qualify as a measurement.

Measurement Device. Any system with the ability to absorb a quantum of energy, analyze the instantaneous properties of the absorbed energy at the point in time and space of absorption, and record those properties as outcomes with defined values. Both natural and engineered systems can qualify as a measurement device.

Along with the definitions of energy exchange dynamics in §3.2, WEX grounds measurement entirely in operational definitions connected to the formalisms, the Standard Model, and two indisputable facts about the natural world.

- Energy exchange occurs at all scales of the universe
- Both natural and engineered systems can emit and/or absorb energy

Independent energy exchange between natural systems can qualify as a measurement. An example is a photon emitted by the sun and absorbed by a photoreceptor neuron in the human eye.

The coupling properties of photoreceptor neurons to photons in the visible light spectrum form a natural measurement device. The neurons absorb photons, analyze their properties, and record those properties in synapses for the brain to interpret as visual information.

Engineered measurement devices are designed with specific coupling mechanisms to absorb targeted energy quanta emitted by quantum systems, analyze the properties of the absorbed energy, and record the values of the properties in memory and/or display screens. A photographic plate is engineered with materials and couplings designed to capture location information. A Geiger counter is engineered with ionization chambers that register emitted radiation to identify atomic decay events. A Stern-Gerlach apparatus is engineered to capture spin and location information. All scientific instruments engineered to measure quantum systems are specifically designed to couple with and absorb specific quanta of energy, analyze the instantaneous properties of the absorbed energy, and record the values of those properties as defined outcomes.

The weak interaction is not a measurement because it is a unifying energy exchange, not an independent one. The probe becomes part of a measurement only when it later undergoes an independent energy exchange with a measurement device. All of the energy exchanged between the probe and system being studied is retained within the unified wave packet of the combined system (§7). A wave packet that exchanges a sub-quantum amount of energy with any object unifies with that object, altering the resulting unified wave packet structure without qualifying as a measurement. A measurement requires an independent energy exchange to qualify, and definite outcomes require a measurement.

The third sentence in the measurement definition guards against conceptual confusion about a possible role for human consciousness in measurement. A photoreceptor neuron in the human eye that absorbs a photon emitted by the sun qualifies as a measurement because it is directly involved in the energy exchange event, while a photoreceptor neuron absorbing a photon emitted from the display on a scientific instrument has no direct physical interaction with the energy exchange registered by the instrument, thus does not qualify as a measurement in this context. This distinction is essential to resolving paradoxes in §9.

The compatibility of structural features between a wave packet and measurement device determines whether they can couple and exchange energy. For example, an ultraviolet light detector will not couple with light at infrared frequencies. Engineered measurement devices are designed to couple with and absorb wave packets with specific structures, capture and store attributes of the energy absorbed, and display the attributes on a screen or printout, creating the illusion that a particle with defined properties exists when in fact what was captured by the instrument was the energy ‘signature’ of an absorbed wave packet.

3.4 Outcome Values

Since wave packets contain no form of value in WEX, outcome values are defined by the measurement devices that capture and analyze the attributes of independent energy exchanges, leading to two more definitions:

> **Particle Signature.** The point-in-time snapshot of the attributes of a quantum of energy emitted by a wave packet and absorbed by a measurement device. Particle signatures are evidence of an energy exchange event, not physical entities that exist in nature.

Classical Information. Defined property values that are produced by analyzing a particle signature and representing them in terms of the variables used in physics models (e.g., position, momentum, spin, and polarization). The measurement device's coupling properties and the variables sought determine how the absorbed energy is represented as defined values derived from a particle signature.

‘Classical Information' is equivalent to 'Observable Values' as a description of measurement outcomes, but the two terms carry different ontological commitments. In standard quantum theory, observable values are derived from observables, mathematical operators with eigenvalue spectra in the formalisms. Meanwhile classical information is ‘produced’ by scientific instruments (not ‘discovered’) when the instrument analyzes a particle signature and records its attributes in quantities defined by the variables used in physics. WEX prefers the term ‘classical information’ because its meaning is clear and unambiguous. Observable Value is so deeply connected to Observables in standard quantum physics that using the term could mislead readers to think some form of value exists in wave packets prior to measurement, which WEX rules out. Meanwhile no reader will assume that anything defined as ‘classical’ exists in wave packets prior to measurement.

Energy and angular momentum illustrate how structural features constrain what classical information is defined in a particle signature. A wave packet's rest energy, equivalent to its mass, is an identity feature shared by every wave packet of its species. Its total energy pattern includes dynamical features that evolve between energy exchanges, such as when a wave packet’s axis of energy rotation precesses in a magnetic field. [22] Measured energy and spin values are classical information defined by a measurement device and contained in a particle signature. The signature contains the amount of energy exchanged and the spin value along the device's measurement axis as a point-in-time snapshot of the exchange, not values the wave packet held before measurement. Spin values along different measurement axes cannot be defined simultaneously, since each requires its own exchange with a device configured for that axis.

Particle signature is identical to ‘energy signature’ mentioned earlier. The use of the word 'particle' here is the one remnant of particle language that WEX intentionally retains for clarity purposes only. Particle signature corresponds precisely to the detection events the Standard Model attributes to elementary particles, but with a different ontological commitment. The name 'Standard Model of Elementary Particles' suggests that elementary particles physically exist, while under WEX, a particle signature is simply a record of an independent energy exchange event, not a physical entity that exists in nature. The term ‘particle signature’ therefore provides a natural reminder throughout the paper that what the Standard Model calls an elementary particle is the fleeting signature of an independent energy exchange in WEX that creates the illusion that a particle exists. Particle signatures are empirical evidence of energy exchange events, not evidence of objects with measurable properties that exist before, during, or after measurement.

Wave packet unification produces no particle signature thus produces no classical information. Sections 5 through 8 elaborate on this in the WEX treatment of entanglement, EPR correlations, weak measurement, double-slit, and delayed choice experiments.

Particles with precise values do not exist in WEX. The intrinsic wave nature of matter embedded in the WEX principle suggests that what we think of as elementary particles are illusions. The Standard Model inventories and organizes the empirical particle signatures of

quantized energy exchanges that occur between independent quantum systems.

3.5 Model Scope

The formalisms are abstract mathematical models that describe physically real wave packet behavior individually or as part of a quantum system. Energy exchange alters the structural features of interacting wave packets, thus requires quantum system models to be reconstructed post-exchange to accurately describe the updated state of the system. This leads to the need for a scoping definition for formalism models.

> **Model Scope.** A mathematical model of a quantum system should include only the components involved in energy exchange up to the moment the exchange begins. Models must be reconstructed after both independent and unifying energy exchanges because any energy exchange alters the dynamical features of the wave packets involved. Including entities that play no role in that exchange adds unnecessary complexity to a model.

Including observers and other objects that play no role in an energy exchange adds complexity without adding physics. Measurement devices are excluded because wave functions model the system only up to the moment it starts exchanging energy with a measurement device, so measurement devices lie at the boundary of a wave function's scope rather than within it. After the exchange, the wave function must be reconstructed to describe the updated system. Scoping wave functions around energy exchange in this way is the central argument resolving Schrödinger's Cat and nested observer paradoxes (§9).

3.6 Comments on the WEX Principle and Definitions

WEX is a claim about definition, not discovery. Observables, what the standard formalism represents as operators with eigenvalue spectra (e.g., position, momentum, spin, polarization), have no value whatsoever until an energy exchange with a measurement device defines one. This energy exchange does not reveal values that were already there in some form, rather they are produced by measurement devices. When a scientific instrument absorbs a quantum of energy, it analyzes the properties of the energy pattern at a specific point in time and space. It essentially takes a point-in-time ‘snapshot’ of the absorbed energy pattern and converts its attributes into specific values for position, energy, momentum, spin, and polarization. Particles with defined property values are extracted from the point-in-time ‘energy signatures’ of absorption events, thus are evidence of quantized energy exchange rather than evidence of a particle with defined properties that existed before the measurement. This is the sense in which WEX views particles as illusions rather than fundamental entities existing in nature.

WEX explicitly rejects hidden and partial values. There is no value that is fractionally defined, no state in which a wave packet partly has a value, no form of value ever exists in a wave packet. WEX explicitly rejects the vocabulary of intermediate and partial values entirely, on the grounds that such language smuggles in the idea that a fraction of a value, a hidden value, or a hidden particle with any properties whatsoever can exist. It does not. Section 7 shows that this absolute strictness in definition is what allows weak measurement to be understood cleanly rather than being a challenge to the WEX principle.

Measurement devices define property values. Scientific instruments that function as measurement devices are designed to couple with wave packets, absorb specific quanta of energy from them, analyze the various attributes of the absorbed energy, correlate the attributes to variables used in physics as property values, record the magnitudes of the property values and

store them in device memory, and present the values on an output display or printout. This process creates the illusion that a particle with defined properties existed before measurement and was absorbed by the measurement device. Under WEX, a measurement device absorbs a quantum of energy and produces a particle signature with assigned property values that reflect the attributes of the absorbed energy.

WEX 'partially' resolves the measurement problem. Standard quantum theory lacks an account of the instant its indeterminate equations produce outcomes with precisely defined values at precise locations in space, the central mystery in quantum physics known as the measurement problem. [26,27] That values are 'precisely defined by' independent energy exchange that produces particle signatures addresses part of the measurement problem, as does the account of why each exchange yields a single definite record (§4.2), but WEX does not explain where one of the probabilistic locations defined by the Born rule will host an energy exchange event. WEX inherits the Standard Model's allowed quanta and the Born rule and does not aim to derive them. Whether a deeper mechanism governs where an individual exchange occurs is left open.

WEX is formalism agnostic. It is independent of mathematical language because it focuses on the shared features across quantum formalisms. This is no different from the earth's surface being independent of whether it is mapped with a Mercator or a polar projection, or whether its features are measured using imperial or metric units. Since WEX is formalism agnostic, it adds nothing mathematical to quantum theory: no new equations, constants, dimensions, variables, or modifications to the Born rule. Every empirical prediction of quantum theory is therefore a prediction of WEX, and any experiment falsifying standard quantum mechanics would falsify WEX. Its claims concern the fundamental entities the formalisms model, not the mathematical descriptions of their behavior. The paper contains no mathematics as prose alone is sufficient to define WEX and trace its consequences.

WEX rejects wave-particle duality. Every formalism predicts the wave-like behavior of fundamental entities with discrete, localized outcomes resulting from energy exchanges in the physical universe. What appears as a particle during measurement is not described by ten of the eleven formalisms as having any defined values in the physical universe before measurement. Pilot-wave theory is the sole exception, but only for particle positions by design of the formalism.

WEX rejects superposition as a physical state of particles or properties existing before measurement. It retains only the linear combination of superposed waves, the adding of wave amplitudes that produces interference, which every formalism predicts and which WEX relies upon. Wave packets are singular extended entities that cannot exist in multiple places simultaneously. Neither particles nor the properties defined in particle signatures exist before measurement, so no superposition of any particle or property can exist. Superposition in this sense is an artifact of the wave-particle duality view and thus is rejected as incoherent in WEX.

4. First Consequence: Localization Without an Ad Hoc Collapse Postulate

Most formalisms require a collapse postulate because they lack a physical mechanism for wave packet localization. The collapse postulate asserts that measurement causes wave functions (or other core mathematical objects) to collapse instantaneously to a single state with a defined property value. This postulate is "ad hoc" in the strictest sense: it introduces an undefined process with no connection to the formalisms, contradicts unitary evolution, and serves no role except to

make predictions agree with observation. It is imposed from outside the theoretical framework, not derived from it.

4.1 Why Standard Quantum Theory Needs a Collapse Postulate

Standard quantum mechanics describes wave function evolution through the Schrödinger equation, which is linear and unitary. Unitary evolution preserves superposition: a wave packet described by a linear combination of eigenstates will remain in superposition indefinitely. Yet measurement produces definite outcomes at specific locations in physical reality. How superposed eigenstates collapse into a single definite outcome remains unexplained in quantum theory.

The collapse postulate fills this gap by stipulating that 'measurement' causes the instantaneous collapse from the superposition produced by unitary evolution to a single definite result. But this postulate simply introduces an ad hoc mechanism which:

- Is not derivable from any formalism's core equations
- Ends unitary evolution without providing explanatory physics
- Fails to define what constitutes a measurement
- Fails to define what constitutes a measurement device that can trigger collapse
- Leaves open the possibility that merely observing a quantum system can trigger collapse without any physical interaction

The postulate is necessary precisely because quantum mechanics has no physical mechanism to explain localization. Without it, unitary evolution can never yield localized results with defined values.

4.2 Energy Exchange Physics Makes the Collapse Postulate Unnecessary

WEX does not require a collapse postulate because it grounds localization in the physics of energy exchange and the definitions supplied in §3 for energy exchange and model scope. The physics is the energy exchange itself, which alters the physical structure of both systems. The consequence for any mathematical model is that the equations written for a system before an exchange no longer describe it afterward, so the model must be rebuilt. This is true of every model of every system at every scale. Since system models must be reconstructed after each energy exchange, wave function collapse can best be understood by flipping the conventional view on its head. Collapse is not an externally imposed process that causes definite results to appear. Energy exchange causes wave functions to 'collapse in their usefulness' in describing the post-exchange state of the system. A measurement device couples to a quantum system and absorbs a quantum of its energy, after which the wave function model must be reconstructed to represent the updated state of the system. No additional postulate is needed to describe localization events. This does not mean that WEX fully explains localization as it only explains parts of it. Four components of localization are separated below and each is marked by whether WEX gives a physical account of it or inherits it from quantum theory:

- **The localization event (physical account in WEX).** An independent energy exchange between a wave packet and a measurement device, which occurs when their structures are sufficiently compatible to couple and exchange a quantum of energy.

- **The model update (physical account in WEX).** The reconstruction of a formalism model to describe a quantum system after any form of energy exchange (§3.5).
- **The single definite record (physical account in WEX).** A quantum is exchanged whole, so a measurement device absorbs it as one particle signature and no further energy remains to be absorbed elsewhere. How a wave packet concentrates a full quantum at the exchange location is described in §6.4.
- **The location and its probability (inherited).** The probability that an independent energy exchange occurs at any given location comes from the Born rule, and the size of the quantum comes from the Standard Model and rests on Planck's constant h. WEX reads the Born rule physically. For a single wave packet, the probability of an exchange occurring at a location is proportional to the square of the wave packet's amplitude at that location, which for any physical wave is its local energy density. An exchange is therefore more likely to occur where a measurement device couples to more of the wave packet's energy. The same reading extends to unified wave packets, where the Born rule gives joint probabilities for exchanges at more than one location (§6). This is a reading of the Born rule and not a derivation of it. Which location hosts an individual exchange is not determined, and whether a deeper mechanism governs it is left open.

WEX is not alone in attempting to explain various aspects of localization. Other approaches attempt to supply the missing physics through spontaneous collapse, gravitational thresholds, or exchanges between emitters and absorbers.[28,29,30,31] The transactional extension of quantum direct-action electrodynamics offers a physical account of the Born rule's squaring as the product of emission and absorption amplitudes.[21] WEX shares this view of energy exchange as two-sided but remains agnostic on the mechanism involving advanced waves propagating through a quantum substratum on which that account relies. Decoherence explains why interference between alternatives becomes unobservable once a system couples to its environment [27,32,33] but does not itself select which outcome occurs. WEX is agnostic on which of these approaches, if any, supplies that selection.

4.3 Lightning as an Energy Exchange Analogy

Consider the analogy of a lightning bolt as an energy exchange event. Before lightning appears, there are only the voltage differentials between various points in the cloud and earth below. These differentials vary between trillions of points in the cloud and earth where the lightning bolt may appear and exchange energy. A mathematical model could be built that treats the lightning bolt as existing in superposition of many states in infinite dimensional configuration space that describes every possible path the bolt could travel between the cloud and earth. When the coupling conditions between the cloud and earth align (e.g., the voltage differential of one of these paths exceeds the dielectric insulation strength of the atmosphere) energy is exchanged between the earth and cloud in the form of a lightning bolt. The bolt exchanges an amount of energy that can be precisely measured, it travels between two points in the cloud and earth that can be precisely measured, takes a zig-zag path through the atmosphere that can be precisely measured, and quickly disappears once the energy exchange is completed. Lightning bolts are evidence of energy exchange between the cloud and earth that contain precisely defined values in their energy exchange signatures.

The analogy has limits in that a lightning bolt's end points, path, and amount of energy exchanged are in principle determined by atmospheric conditions while WEX leaves where an

independent energy exchange occurs to Born statistics. The energy differential between the earth and cloud existed before the bolt appeared, but neither the lightning bolt, its end points, its path, nor the amount of energy transferred existed before the discharge nor did they persist afterwards. The classical information that quantitatively describes a lightning bolt is defined only when measurement devices register the energy exchange and record its property values as a lightning bolt energy signature.

The lightning bolt did not exist in superposition and contained no hidden values awaiting discovery. A “lightning postulate” is not required to explain the appearance of a lightning bolt with defined property values as energy exchange physics is all that is needed. Similarly, independent energy exchange physics is all that is needed to explain the appearance of particle signatures containing defined values at measurement. No additional postulate beyond energy exchange physics is required in either case. The mathematical model that treated lightning bolts in superposition of many possible lightning bolts collapsed in its usefulness once the lightning bolt appeared, no different from the way a quantum wave function collapses in its usefulness once a wave packet exchanges energy. Localization is evidence of independent energy exchange events and mathematical models of energetic systems at all scales of the universe collapse in their usefulness after energy exchange.

5. Second Consequence: Unified Wave Packets Contain No Values

Wave packet unification is the WEX term for entanglement (§3.2). The standard view of entanglement treats entangled systems as separate particles with some degree of independence and some degree of dependence that enables them to have correlated property values. WEX rejects this view on two points: unifying energy exchange involves a complete loss of independence, and no values ever exist in wave packets to correlate. Most formalisms model entangled wave packets as a single unified mathematical object, which WEX takes literally as meaning the predecessor wave packets have no degree of independence once they merge to form a single unified wave packet. Unification is simply a more precise term for entanglement that avoids the trap of thinking that merged wave packets have any degree of independence. Unifying energy exchange retains all energy within the unified wave packet and no energy is emitted, thus no measurement occurs and no definite outcomes are deduced from a particle signature.

Unification carries no correlated values. The correlations observed in measurement outcomes are correlations between particle signatures, never values carried by a unified wave packet. To say that entanglement "correlates the spin of A with the spin of B" implies that A and B retain some degree of independence and carry correlated spin values. They have neither under WEX.

Unification transfers no classical information. No form of classical information exists until it is defined by a measurement device that produces a particle signature which contains classical information.

Unification produces no partial values. This follows immediately from the principle’s rejection of fractional values, and it is the commitment Section 7 turns on.

The unified packet is the whole of what exists. There is no “joint state.” There is only the “unified state.”

Degree of unification is continuous. The degree of unification is continuous and a function of coupling strength. The formalisms compute it routinely as entanglement entropy (§11) and a weak-

measurement probe (§7) is deliberately engineered to sit near the low end of that range. When two electrons scatter elastically, their momenta cannot be assigned to the electrons individually because the outgoing state is considered a single non-separable state. Under WEX the two wave packets couple while they overlap, share energy within a single structure, and leave as a unified bimodal wave packet. The degree of unification is continuous and set by the coupling strength between the electrons.

Degree of unification is independent of separation. A unified extended bimodal wave packet whose modes are separated by a billion light years may be maximally unified, which is why EPR correlations can survive arbitrary distances (§6). Under WEX the modes are part of a single unified wave packet so there are no separate parts to be far apart.

Unification can be reduced but never reversed. Further energy exchange, whether an independent exchange that produces a particle signature (§6) or a controlled sub-quantum exchange such as those used in quantum computing (§12), can reduce the degree of unification. Each is a new exchange not a reversal of the one that produced the unification. Wave packets that regain independence after unifying have different physical histories than wave packets that never unified, even when no observable difference remains. Wave packet histories cannot be erased (§11).

Unification requires no mechanism beyond energy exchange that results in loss of independence. The mystery of entanglement is largely an artifact of assuming property values existed in the predecessor wave packets, were correlated at unification, and maintain some degree of independence from one another after unification. WEX rejects all three of these assumptions.

6. Third Consequence: Non-Locality Confined to Energy Redistribution

Einstein, Podolsky, and Rosen (EPR) argued in 1935 that quantum theory must be incomplete, because otherwise two particles could act on each other at a distance, violating the local causality embedded in classical theories. [34] Bell's 1964 theorem made the question experimentally testable. [35, 36] Experiments reported violations of Bell's inequalities in 1982 [37] and later experiments closed remaining loopholes. [38] Einstein's hope of explaining the behavior with local hidden variables was ruled out by Bell's theorem and these experiments. The 2022 Nobel Prize in Physics recognized this work.

Bell’s theorem is a mathematical test of assumptions about how correlated measurement outcomes can arise between two spacelike separated measurement locations. Bell’s argument rests on four core assumptions: [39]

1. **Separability:** Two entangled quantum systems can be treated as separate systems.
2. **Locality:** A measurement on one quantum system cannot influence another quantum system faster than light.
3. **Realism:** Quantum systems carry definite values before measurement that determine outcomes. Bell's 1964 argument assumed these values fix outcomes, while his later formulations replaced determinism with local causality. [40,41]
4. **Measurement Independence:** Experimenter choices of what to measure are uncorrelated with the properties of the systems.

The separability assumption does not apply to WEX because unified wave packets lose their

independence and cannot be treated as separate systems (§3.2, §6.1). The locality assumption also does not apply to WEX because there is only one unified wave packet at initial measurement, which fractures the unified packet and constrains its remainder (§6.2). The realism assumption, in its local-causality form, requires a separate complete state for each side of the experiment. A unified wave packet has a single complete state shared by both sides, and it carries no values prior to measurement (§3.4). WEX retains the fourth assumption and does not require a measurement loophole to evade Bell's argument.

Bell's theorem concerns models in which separate systems carry local states that fix the probabilities of their outcomes. WEX accepts the theorem's conclusion for the separate systems it describes, but the fundamental entity in an EPR experiment under WEX is a single non-separable wave packet, so there are not two local states for the theorem's assumptions to apply to. WEX therefore does not violate Bell's theorem as its assumptions simply do not apply to WEX. The non-separable object in WEX is an extended unified wave packet in physical space and time. This retains the non-locality Bell's theorem establishes but locates it in the internal energy dynamics of a single wave packet.

A broader point is that every formalism describes an entangled system with a single joint mathematical object that does not factorize into separate parts (§2, Table 2). This suggests that Bell's separability premise not only does not apply to WEX, it may not apply to entangled systems described by any formalism [39], though non-separability alone does not remove non-locality. [42] Treating entangled systems as separable objects reflects particle ontology over the wave ontology suggested by the common features across formalisms, specifically the shared "non-separable entangled systems" feature.

The relevant non-locality test for WEX is whether it can explain EPR correlations from an extended unified wave packet perspective without invoking non-local influences. It cannot do so entirely, because WEX retains non-local energy redistribution within a single wave packet. WEX therefore does not restore local causality in the Bell sense and does not claim to. The remainder of this section shows that WEX is consistent with the observed Bell violations and confines non-local effects to energy redistribution dynamics within individual wave packets. Energy redistribution is a dynamic that every wave packet has (§3.2), so WEX adds no new kind of non-locality. It relocates the non-locality that Bell's theorem establishes from influences between independent objects to the internal dynamics of one extended object.

6.1 Unified Wave Packets Are Non-Separable

When two wave packets form an entangled system, their energy structures unify to become a single extended wave packet whose structural properties must be derived from the combined structural properties of the predecessor wave packets according to universal conservation laws. The resulting unified wave packet is a single energy pattern that has one geometry, one oscillatory structure, and one angular momentum. It has one set of structural properties and contains no defined values since it is an extended energy pattern that is dynamically evolving in space and time. Any net rotation of its energy pattern has a single axis and handedness, dynamical features of how energy rotates in any wave packet. Conventional EPR pairs are a special case where the unified wave packet has zero net angular momentum, is rotationally symmetric, and its measurement axis is only determined by the detection geometry of the first measurement device it encounters. The structural features of a unified wave packet no longer belong to the predecessor wave packets individually because they completely lose their independence as separate entities

when they unify, and neither can recover its former identity when the unified wave packet is measured.

6.2 Fracture and Conservation

Figure 1 is a schematic representation of a unified wave packet extending in space and approaching a measurement device in the top half of the figure. In the bottom half, an independent energy exchange with a measurement device fractures the unified wave packet into a particle signature and residual wave packet. The particle signature is shown with a dotted line to illustrate that it is not an entity that has physical existence, but an instantaneous record of the energy exchange event.

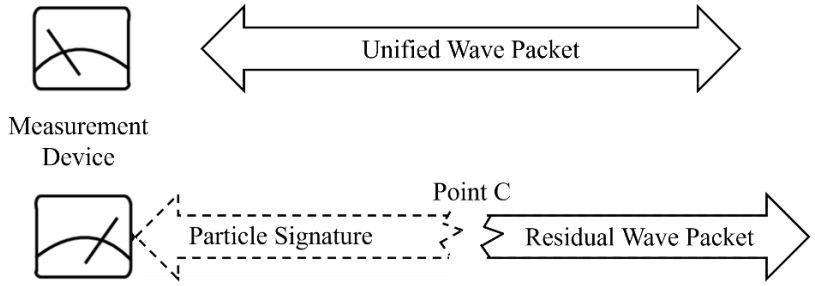


Figure 1: Fracture of a Unified Wave Packet Constrained by Conservation Laws

The signature and residual have complementary dynamical features that together account for the dynamical features of the unified wave packet, just as the pieces of any fractured physical object (e.g., a dinner plate dropped on the floor that breaks into two pieces) will have complementary physical structures that together account for the original unfractured whole. In both cases the possible structures of the broken parts are constrained by the original structure and conservation laws applied at the point of fracture (point C in Figure 1). This is conceptually represented in the figure by the geometry of the signature and residual having complementary jagged edges.

6.3 Why Bell Violations Are Consistent with WEX

Bell's inequalities limit how strongly two outcomes can be correlated when each is determined only by properties on its own side of the experiment and by its own detector setting. WEX outcomes are not determined in this manner. The first independent energy exchange fractures the unified wave packet in Figure 1 and defines the first outcome through the interaction between the unified packet's structural features and the detection geometry of the measurement device. Conservation laws leave the residual wave packet with complementary dynamical features to the particle signature because the structural features of the parts must account for the structural features of the whole. A subsequent measurement of the residual is defined by the residual's structural features and the second measurement device's detection geometry.

The observed spin or polarization correlations between two measurements depend on the relative orientation of the two detection geometries, a relational fact about the unified wave packet's structure constrained by conservation at fracture, not a product of pre-existing values each fractured part carries independently. The correlations are observed because the rotational structures of the energy patterns that were absorbed by the two measurement devices were

complementary due to the conservation of energy, momentum, and angular momentum applied at the point of fracture. The particle signature and residual wave packet will have complementary angular momentum and axes of rotation because they are fractured parts of a single physically real object whose properties were constrained by universal conservation laws at the fracture event. Measurements along any common axis yield complementary values because the wave packets being measured have complementary angular momentum and axes of rotation. They have complementary dynamical features, not complementary values.

Bell's bound follows from independent outcome determination which is not the case under WEX. Correlations that exceed the bound are consistent with WEX because the particle signature and residual wave packet are complementary parts fractured from a unified whole. Conservation at fracture accounts for complementary outcomes when the two detection geometries are aligned. At other settings, WEX inherits the quantitative dependence on detector angle, including the quantum limit on the strength of correlations, from quantum theory as a calculation tool and does not claim to derive it, in the same way it inherits the Born rule and the Standard Model's quanta. WEX supplies the physical reading.

6.4 Where the Non-Locality Resides

Prior to the first independent energy exchange, the unified wave packet carries energy equal to two photon quanta. A full quantum of energy is unlikely to be concentrated at the precise location of any independent energy exchange. A wave packet is made solely of energy and that energy is spread across its extent to give the wave packet a physical structure. Thus, in order to exchange one quantum of energy with the first measurement device, the unified packet must redistribute its internal energy to concentrate a full quantum at the exchange location. The location inside its extended structure where the last bit of sub-quantum energy is gathered to produce a full quantum is denoted as point C in Figure 1. Point C is where the unified packet fractures and conservation laws apply to the fractured parts. Because the energy available to complete the independent energy exchange depends on how energy is spread across the packet, the precise location of point C varies with the unified packet's internal energy pattern at the exact moment of the energy exchange.

The energy exchange with the measurement device and the application of conservation laws at C are both local events. The non-local aspect of WEX is the redistribution of sub-quantum energy from within the unified packet's extent to concentrate a full quantum at the energy exchange location. This non-local redistribution is an internal process occurring within a single extended entity, confining WEX non-locality to the internal energy dynamics within individual wave packets. This redistribution cannot carry a message. WEX inherits the Born rule, under which the outcome statistics at one measurement device do not depend on the setting chosen at the other, and wave packets carry no values that an experimenter could set to encode a message. Both points are consistent with the no-signaling theorem (§6.6).

6.5 Relativity

A residual wave packet exists only after a fracture, so a fracture always precedes any measurement of the residual. If two independent energy exchanges on the same unified wave packet are space-like separated, observers in different frames may disagree about which one fractures the packet. In every reference frame the earlier exchange fractures the packet and the later one measures the residual, with the ordering relative to each frame and no preferred frame, consistent with special relativity. The correlation described in §6.3 is a relational fact about the unified wave packet that depends only on the relative orientation of the two detection geometries.

It is therefore symmetric between the devices and is the same whichever exchange is assigned to be first. The redistribution of energy and the conservation constraint are conditions on a single object, so no speed attaches to either. The description of which exchange fractures the packet depends on the frame, but the measured outcomes and their correlations do not.

6.6 Summary

Bell's separability, locality, and realism assumptions do not apply to a single unified wave packet, so WEX is consistent with Bell's theorem. EPR correlations are consistent with conservation laws constraining the structural features of physically real wave packets upon fracture. WEX does not restore local causality in Bell's sense. It relocates non-locality from influences between independent objects to the internal energy dynamics within individual wave packets, a dynamic that every wave packet has. Observers in different reference frames may disagree about which exchange fractures the unified packet, but not about the outcomes and their correlations. The inherited Born rule keeps the outcome statistics at each device independent of the setting at the other, and wave packets carry no values that could encode a message, consistent with the no-signaling theorem. The PBR theorem rules out purely epistemic readings of the quantum state for models that satisfy preparation independence. The theorem constrains what the quantum state is (§11) and says nothing directly about the redistribution. [43] WEX is consistent with it because the quantum state is a mathematical model of a physically real wave packet, and the internal redistribution is a dynamic of that wave packet, not of the model (§11).

7. Fourth Consequence: Weak Measurement Defines No Values

Weak measurement may be the sharpest test of the WEX principle, and it is worth stating the challenge at full strength before answering it. The conventional view is that weak measurement couples a probe to a system with arbitrarily small interaction strength, yielding classical information about the system while leaving the system largely undisturbed. If classical information is truly obtained by weak measurement, then a value would be defined without an independent energy exchange that produces a particle signature, which would falsify the WEX principle. [44,45]

The WEX response is that the probe acquires no value during the weak interaction. Not a partial value. Not a degraded value. Not a hidden value. No value whatsoever. What occurs during the weak interaction is minimal unification at the low end of the continuous range described in §5.

Consider probe X and system Y which exchange a sub-quantum amount of energy, forming unified wave packet XY. Energy redistributes within the unified wave packet as it does within any wave packet as it evolves through time. This internal redistribution does not result in quantum energy being emitted by unified packet XY, so no particle signature is produced and no values are defined. The probe's values are only defined when it subsequently undergoes an independent energy exchange with a measurement device that produces a particle signature. Measurement of probe X accomplishes two things simultaneously: it defines classical information in X's particle signature AND constrains the residual wave packet through conservation laws to be complementary to X's particle signature, no different from the discussion on fractured unified wave packets in §6.2.

A concrete example may be helpful. A weak photon probe couples to an electron being studied, forming a minimally unified wave packet. When the weak probe photon subsequently strikes a detector, the particle signature defines the photon's values (location, energy, polarization). Simultaneously, the fractured unified packet constrains the residual electron wave packet structure

through conservation of momentum, energy, and angular momentum to produce values correlated with the probe's particle signature to a degree set by the degree of unification (weak when the coupling is weak) when the electron is subsequently measured. The values were not extracted from the electron by the weak probe but were defined when the probe was measured and constrained what future measurements of the electron will reveal. Under WEX, weak measurement does not capture classical information about a quantum system being studied, it changes and constrains the system being studied.

This account of weak measurement is consistent with empirical results and is where the strictness of WEX rejecting any form or degree of value existing in wave packets earns its keep. A weaker position that concedes any form of value exists in wave packets before measurement would falsify the WEX principle thus the strict position is more defensible, not less.

Minimal disturbance. The system is minimally disturbed because the unifying energy exchange is minimal, resulting in probe and system forming a minimally unified wave packet. Minimally unified does not imply there is any degree of independence. It simply means unified wave packet XY has minimal entanglement entropy.

Anomalous weak values. Weak values lying outside the eigenvalue spectrum of the measured values are often treated as puzzling in the conventional view but are unproblematic under WEX. They are not values of anything during the weak interaction but result from computing the statistics of particle signatures over an ensemble with post-selection, a computational artifact under WEX that describes no aspect of unified or residual wave packets. [46,47]

Post-selection. Post-selection requires only that the system eventually undergoes a measurement that yields a definite outcome, which it does under WEX. Conditioning an ensemble on a later outcome is a procedure for selecting a subset of runs. WEX does not allow an outcome value to exist before an energy exchange defines one, hence there is no pre-existing outcome to select from. This is a variation of no retro-causation in the delayed-choice experiments in §8.2.

The calculation mechanism of weak measurement is untouched. Under WEX it describes structural features of the unified wave packet that constrain the particle signatures of probe and system to be complementary when measured. WEX does not need to address partial values because there are none. WEX is consistent with the weak-value statistics and does not claim to derive them. It offers a physical reading of why they arise. The conventional reading treats a weak value as a property the system has during the weak interaction, which WEX rejects because no value exists until an independent energy exchange produces a particle signature.

Average Trajectories Example. In the average-trajectory experiment [46], a weak coupling at a chosen plane downstream of a double slit is followed by a strong measurement of each photon's final position. Under WEX each photon is a single extended wave packet. At the chosen plane the weak coupling is a unifying energy exchange that forms a minimally unified wave packet, thus defines no value. The only independent energy exchange occurs when the photon is absorbed at the final detector, and the resulting particle signature defines the final position together with the readings of the weak coupling. Sorting those readings by final position and averaging over many photons produces the reported average trajectories. The curves are statistics over particle signatures. They do not describe a path that any individual photon followed nor any position that any photon had at the chosen plane because neither exists in WEX. WEX does not calculate the weak values but offers a physical reading of how the averaged curves arise from particle signatures even though no value existed at the chosen plane.

8. Fifth Consequence: One Description of Extended Structures

The WEX principle describes all forms of spatially extended wave packets similarly, independent of their total energy.

8.1 The double-slit experiment

A photon wave packet emitted from a source will spread out over the region between source and the double slit barrier, pass through both slits, and emerge as a bimodal wave packet that interferes with itself as it approaches the screen. On reaching the screen the packet undergoes an independent energy exchange with the screen and produces a particle signature somewhere on the screen. The screen functions as a measurement device (§3.3) and successive wave packets produce particle signatures distributed on the screen according to Born statistics for a single self-interfering wave packet, yielding the classic interference pattern. [48] The screen is engineered with structural and coupling properties designed to absorb photons and produce particle signatures anywhere on the screen, resulting in classical information on energy exchange locations for successive energy exchanges.

If absorptive photon detectors are placed at the slits, they will function as additional measurement devices that absorb the photon's energy at one or the other slit, thus no interference pattern appears on the screen. Traditionally this is viewed as revealing the particle nature of reality while WEX views it as evidence of an energy exchange that produced a particle signature at one of the slits. Either slit detector will fully absorb the photon's quantum of energy, leaving no residual energy to exchange with the other slit detector or the screen, thus no impacts appear on the screen, and no interference pattern builds up. The wave packet has some probability of undergoing an energy exchange at each detector, defined by the Born rule applied to the amplitude of the wave packet at each slit.

If one slit is blocked the wave packets pass through the unblocked slit, spread out as they emerge from the slit, impact the screen and the screen does not build up a two-slit interference pattern because the wave packets were not bimodal thus could not interfere with themselves. WEX accounts for the standard double slit results in a straightforward manner where a single extended wave packet passes through both slits and exchanges its energy with the first measurement device it encounters.

8.2 Wheeler's delayed-choice double-slit experiment

In Wheeler's thought experiment, the choice of how to detect a photon is made after the photon has passed the point where it seems to have committed to one path or both. A stream of photons passes through a double slit apparatus and builds up an interference pattern on a screen, suggesting each photon travels through both slits. If the screen is removed, each photon is instead absorbed by one of two telescopes aimed at different slits, resulting in 'which-slit' information about the slit each photon traveled through. Quantum theory predicts that the screen can be randomly removed after each photon has passed the slits, and the results will still produce interference if the screen is not removed and which-slit information when it is removed. The question is how a later choice could determine whether the photon behaves as a wave or a particle, a scenario often viewed as possible evidence of retro-causality.

Under WEX, each photon is a single coherent wave packet that always passes through both slits and forms an extended bi-modal wave packet on the other side of the double slit barrier. The only

question is whether the wave packet encounters a measurement device that absorbs its quantum with or without sorting its energy by slit.

The two modes begin to overlap after the wave packet passes through the slits, and the overlapping region carries an interference pattern created as the energy patterns in each mode constructively and destructively interfere with each other. The screen absorbs a steady stream of quanta at locations predicted by Born rule statistics, and the particle signatures accumulate into an interference pattern. Additional screens placed anywhere the modes overlap would record the same pattern, including if two screens were to replace the two telescopes.

Each telescope lens focuses light arriving from the slit it is aimed at onto its detector while focusing light from other directions away from its detector. Each telescope detector can therefore only absorb energy from the portion of the wave packet arriving directly from its slit. As discussed in §6.4, an independent energy exchange draws a full quantum from the extended packet and concentrates it at the point of exchange. Every particle signature the telescopes record is thus a which-slit result that can never contribute to an interference pattern. Which-slit information does not exist because the photon always travels through both slits. The which-slit information that appears in the experiment is a function of the detection geometry of the telescopes, not evidence that the wave packet passed through one or the other slit. Each measurement device produces the classical information its detection geometry was designed to capture.

The delayed choice prediction was later confirmed with single photons traveling through a two-arm interferometer. [49,50] Each photon is split into two beams with perpendicular polarizations traveling separate paths. Mirrors bring the beams back to a common point, and two detectors sit just past the convergence point. After each photon enters the interferometer, a quantum random number generator decides whether to bring the two beams back into the same polarization before they reach the detectors. Interference appears when the polarizations match, and 'which-path' information appears when the polarizations are perpendicular.

Under WEX, each photon is a single bi-modal wave packet that always travels both paths. If the modes have perpendicular polarization at measurement, they will not interfere and 'which-path' information results. If the modes have the same polarization at measurement, interference will appear. The random number generator determines which result appears at measurement.

In both experiments there is only one extended bi-modal wave packet, one energy exchange, and one particle signature which defines one value in each trial. There is never an earlier fact for a later choice to overturn so the predicted results are consistent with WEX without retro-causality. Variants in which the choice is made on an entangled partner, as in the delayed-choice quantum eraser experiment, [51] simply apply the same reasoning to unified wave packets rather than individual photon wave packets. The correlations appear only when outcomes are sorted by a later measurement, as described in §7 and §11.

Other readings of these experiments exist. Bohmian mechanics avoids retro-causality by giving the photon a definite trajectory guided by the wave function. Retrocausal and transactional accounts let a later boundary condition or absorber influence earlier events. The single-photon interferometer experiment [49] and the quantum eraser variants [51] are consistent with all of these readings, so they do not discriminate among them.

8.3 The common structure of extended wave packets

The single-photon double-slit, delayed choice double-slit, and unified wave packet (§6) can be understood using the same structural dynamics of extended wave packets at measurement. In all three, an independent energy exchange occurring anywhere within a wave packet's extended bimodal structure exchanges a single quantum of energy at the location of measurement, constraining the remainder through conservation laws. There is no residual energy left after the energy exchange in the single-photon double slit and delayed choice variant, while a residual quantum of energy remains in the unified two-photon case. This reflects a difference in total energy of the wave packets, not difference in principle. A photon passing through a double-slit apparatus carries one photon quantum of energy while the unified packet carries two photon quanta of energy, both having their energy concentrated in the modes of a single coherent extended bimodal structure. The same rule governs both: a single coherent, spatially extended wave packet undergoes a localized energy exchange of a single photon quantum with its total energy conserved. Standard quantum mechanics treats double-slit wave packets and entangled pairs as distinct phenomena while WEX offers a single description of both.

What differs is how the structure became extended. In the single photon double-slit case, the extension is self-coherent, the two modes remaining one structure throughout the apparatus. In the unified two-photon case the connection is a structural feature of the unified packet fixed at pair creation, consistent with EPR correlations surviving distances far exceeding any realistic coherence length. Despite becoming extended via different mechanisms, all extended packets share similar structural dynamics.

9. Sixth Consequence: Observer Paradoxes Dissolve

The paradoxes of Schrödinger's Cat, Wigner's Friend, and Frauchiger-Renner arise from a common source: the absence of a rule specifying what belongs inside a quantum system when constructing a wave function to model the system. WEX defines such a rule around energy exchange and repeats it here for convenience as it is central to resolving observer paradoxes.

> **Model Scope (§3.5).** A mathematical model of a quantum system should include only the components involved in energy exchange up to the moment the exchange begins. Models must be reconstructed after any form of energy exchange because the exchange alters the dynamical features of the wave packets involved. Including entities that play no role in the energy exchange adds unnecessary complexity to a model.

Schrödinger's Cat. The setup places a cat inside a box with a radioactive atom, a Geiger counter, and a vial of poison. If the Geiger counter detects the atom's decay, it triggers a mechanism that breaks the vial, releases the poison, and kills the cat. [52] Standard quantum theory leaves unclear whether the cat qualifies as an 'observer' (i.e. measurement device) and offers no guidance on which side of an undefined quantum-classical boundary the cat lies. The paradox emerges when the cat is included in a wave function modeling the system, leading to the cat being in "superposition" of alive and dead simultaneously until the box is opened.

WEX notes that the undefined terms traditionally used in these paradoxes (observer, measurement device, and model scope) lead directly to the paradox. WEX retires 'observer' and provides precise definitions for measurement device and model scope, which together offer a resolution of this paradox.

Only the atom should be included in a wave function describing the system because it is the only entity in the box *involved in energy exchange up to the moment the exchange begins*. The atom's decay is driven solely by its own internal energy dynamics. The Geiger counter, cat, vial, and mechanism to release the poison should be excluded from the system wave function because the wave function must be reconstructed once the atom begins to emit energy as it decays. From a practical standpoint wave function reconstruction should occur as soon as the Geiger counter begins registering the decay event. Everything that occurs after this point is no longer described by the original system wave function which has collapsed in its usefulness.

Under WEX the cat is always alive or dead, never in superposition of both. The atom's wave function describes the only relevant energy exchange that determines the fate of the cat, decaying according to Born rule statistics. Constructing a wave function that includes anything more than the atom adds unnecessary complexity because once the atom begins to decay the wave function must be reconstructed.

Nested observers. Wigner's Friend and Frauchiger-Renner extend the Schrödinger Cat paradox by nesting observers which creates even more complex paradoxes. Most analyses of the Frauchiger-Renner thought experiment conclude that one of the following three core assumptions underpinning the foundations of quantum theory must be incorrect. [53]

- **Universality.** Quantum theory can be applied to everything, including observers and measurement devices.
- **Consistency.** Two physicists performing the same calculations on a system agree on the resulting statistical predictions.
- **Single Outcomes.** Each physicist who performs a measurement obtains a single definite result.

The WEX model scope argument offered for Schrödinger's Cat applies equally to any paradox that includes nested observers and/or nested measurement devices in a system's wave function, including Wigner's Friend and Frauchiger-Renner. WEX narrows the Universality assumption in quantum foundations by explicitly excluding measurement devices (and by extension, observers) from wave functions while its wave packet realism vantage point affirms the Consistency and Single Outcome assumptions.

10. Seventh Consequence: No Quantum Boundary

If the intrinsic nature of reality is wave-like as asserted in WEX, then there is no need for a boundary at which quantum dynamics cease to apply. The exclusion of measurement devices from wave functions does not imply that a boundary exists between a hypothetical quantum and classical world at measurement. It is simply a model scope rule to efficiently define what a wave function can coherently describe before requiring reconstruction.

Experimental work supports the absence of a boundary. Organic molecules with thousands of atoms have illustrated the intrinsic wave nature of reality at the molecular scale. [54,55] Micro-mechanical resonators of trillions of atoms have shown collective vibrational states at scales visible under a microscope. [56] Quantum biology has reported possible evidence of quantum effects at molecular and cellular scales in living organisms, including coherent energy transfer in photosynthesis [57] and in retinal proteins that migratory birds appear to use for magnetic navigation. [58]

Standard physics models a Bose-Einstein condensate as a single macroscopic wave function, which WEX views as a macroscopic wave packet. Two condensates formed in separate wells that are allowed to overlap will produce high-contrast interference fringes in the overlap region. [59] Under WEX, the overlap region is where the two condensate wave packets unify, and the interference pattern is carried in that unified region. This is consistent with wave behavior and unification in macroscopic matter.

Environmental energy exchanges in macroscopic systems make it difficult for measurement apparatus to discriminate and absorb the specific energy quanta being investigated. But environmental noise does not imply the cessation of wave packet energy exchange dynamics at any scale. [27,32,33] Standard quantum physics, condensed matter physics, plasma physics, classical physics, chemistry, and biology are all powered by wave packet energy exchange between subatomic particles, quasiparticles, atoms, molecules, cells, brains, and stars. The WEX principle asserts there is no scale boundary where quantum dynamics cease. Wave packet energy exchange occurs constantly in all matter structures at all scales. The only limitation in demonstrating the intrinsic wave nature of reality in larger structures is the measurement apparatus's ability to discriminate independent energy exchanges against the backdrop of increasing environmental noise as matter structures increase in scale.

Plasma physics extends the same point to astronomical scales. Stars and the solar wind are plasmas, described by collective waves such as plasma oscillations and Alfvén waves, and by resonant energy exchange between those waves and the electron and ion wave packets of the plasma. Landau damping is the standard example: it was predicted in 1946 and directly measured in laboratory plasma waves in 1964. [60] WEX reads this as ordinary wave packet energy exchange at a scale where individual quantum exchanges cannot be resolved against the backdrop of environmental noise. The WEX principle does not depend on resolving them, but the same limitation means plasma physics can illustrate wave packet energy exchange dynamics at large scales without distinguishing WEX from standard interpretations. Stellar interiors offer indirect evidence of quantum dynamics at extreme scales since fusion in stellar cores depends on quantum tunneling despite intense heat and density. Quantum dynamics are therefore not extinguished by extreme conditions, which raises questions regarding the blanket assumption that the wet, warm, and electromagnetically noisy environments of biological tissues cannot support quantum effects. WEX holds that the sole fundamental constituents of physical reality are physically real wave packets whose energy exchange dynamics are not bounded by scale. That these dynamics have not yet been demonstrated at any given scale does not mean they do not exist there.

Condensed matter physics offers a further illustration. Dense phases of matter are described through quantized collective excitations, conventionally called quasiparticles, whose properties are fixed by the collective structure of the system rather than by any single constituent. Semiclassical theories even treat electrons in crystals as wave packets with structure-derived properties such as Berry curvature and orbital magnetic moment. [61,62] Standard physics treats these as effective descriptions emerging from interacting atoms and electrons. WEX views them as quantized excitations of complex unified wave packet structures. A guitar string offers a useful comparison. The string is a single physical structure with natural modes of vibration. Plucking or damping the string moves energy into or out of its harmonic modes. A crystal lattice is likewise a single unified structure, and a phonon is not a particle traveling through it but a unit of energy in one of its resonant vibrational modes. The quantum version adds that energy can enter or leave each mode only in discrete units set by the mode itself, so every energy exchange with a probe or

detector transfers discrete quanta. The particle-like appearance of quasiparticles is therefore the same as that of elementary particles: a particle signature recording a quantized energy exchange. As with the fractional charges discussed in §3.2, the structural features and coupling properties of interacting systems determine the quanta that can be exchanged. Standard descriptions already account for the data, so the WEX reading is consistent with condensed matter physics rather than evidence for WEX, but it extends its no-boundary argument to some of the most complex collective quantum systems known to science.

A final argument for scale independence comes from black holes. Quantum field theory in curved spacetime predicts the horizons of black holes will emit thermal radiation, suggesting quantum dynamics are even predicted in the most massive objects in the known universe. [63]

11. Eighth Consequence: Quantum Information Theory is the Study of Classical Information Production, Not Quantum Information Discovery

Quantum Information Theory (QIT) studies how quantum systems encode, process, and transmit information. The field treats 'quantum information' as encoded in quantum states, conventionally defined abstractly in Hilbert space independent of how a system is physically implemented. It treats wave functions as mathematical representations of a system's quantum information, the state that quantum operations process. QIT therefore offers no definition of quantum information independent of the abstract mathematics of the formalisms, as it is identified only with a mathematical state and its transformations.

A theorem on the reality of the quantum state shows that any model in which quantum states represent mere information about an underlying reality contradicts the predictions of quantum theory, provided the model satisfies preparation independence. [43] If preparation independence holds, quantum states cannot be mere information but must correspond to something physically real. The abstract mathematics of Hilbert space models wave packet behavior with remarkable accuracy, which is why every result of QIT holds, but it is not an accurate depiction of wave packets in physical reality (§2). What physical reality quantum states refer to in QIT remains an open question, and WEX provides an answer: Quantum states are mathematical representations of physically real wave packets and not the wave packets themselves. This is consistent with the theorem's exclusion of purely epistemic readings of the quantum state, since a model of a physically real object is not mere information about it. What the theorem does not settle is whether the quantum state is the ontic object itself or a model of it, and WEX takes the second view.

WEX rejects the idea that quantum information exists in wave packets because no values of any form exist in wave packets. Information is neither fundamental nor a feature of wave packets. Information is expressed in the variables defined by physics models and produced by measurement devices which map the properties of energy exchange signatures to these variables. What changes is QIT's subject matter, not its results. QIT describes how wave packet structure constrains energy exchange to determine which measurement outcomes are possible. It is the science of controlled classical information production, not quantum information discovery.

Entanglement entropy is a number assigned to degree of unification, a dynamical feature of wave packets in the sense described in §3.1. It is a tool for analyzing unified wave packet structure, not a value the wave packet carries nor a measure of latent correlations since no values exist in wave packets to correlate. Degree of unification is continuous and independent of spatial separation. No single energy exchange defines it, rather it is inferred from the statistics of many

exchanges with identically prepared wave packets and persists until a further exchange alters it. Exchanges can reduce the degree of unification (e.g., when quantum algorithms disentangle qubits), but they cannot undo the energy exchanges that unified the packet. Every energy exchange alters the exchange partners that drive it, such as the control fields that operate on qubits, and that history persists even when the qubits themselves are restored to an unentangled state.

Holevo's theorem states that n qubits yield at most n classical bits of information. One common reading treats this as a limit on how many classical bits can be extracted from a vast array of hidden quantum information. Under WEX, a wave packet's structural features constrain the maximum number of independent energy exchanges that are possible, thus the maximum number of particle signatures that can be produced containing classical bits of information. The Holevo bound relates to how many classical bits can be extracted from a given wave packet's energy pattern, making it a physically intuitive metric rather than a mysterious one. [64]

Teleportation transfers the structural features of one wave packet to another without either one traveling between sender and receiver. The sender and receiver share a unified bi-modal wave packet, and the sender brings the packet to be teleported into coherent overlap with the sender's mode, unifying all three. The sender performs a joint measurement which fractures the tri-modal packet. The detection geometry of the sender's device registers the relative polarization and phase between the two measured modes, and the resulting pair of particle signatures encode that relation as two classical bits which carry no information about the teleported structure. Because conservation at fracture ties the receiver's residual mode to that same relation (§6.2), the bits, sent at light speed, tell the receiver which of four controlled energy exchanges to apply, after which the residual takes on the structure of the teleported packet. [65] The structure moves through the unified packet, never through the classical channel, and the teleported packet's features do not survive the joint measurement, so the structure is transferred, never copied.

Entanglement swapping applies the same logic to two unified wave packets. [66] Wave packets A and B unify to form bi-modal wave packet AB, and C and D unify to form CD. The B and C modes travel to a joint measurement apparatus while the A and D modes head elsewhere. At the apparatus, the B and C modes coherently overlap, and a unifying energy exchange unifies all four modes into a single wave packet, ABCD. A joint measurement of the B and C modes then fractures ABCD, and, as in teleportation, the detection geometry registers the relative polarization and phase between them as two classical bits. The fracture leaves a residual unified bi-modal wave packet spanning the regions where A and D were headed, even though A and D never interacted, and the two bits identify which of four relations its modes bear to each other. That residual cannot be said to carry the identities of A and D, because predecessor identities are lost in unification. If the A or D mode is measured first, that measurement fractures AB or CD before ABCD can form, so no unified packet ever spans those regions. The B and C residuals then carry structures complementary to the earlier signatures, and the joint measurement registers the relation between them. In both cases, correlations between the A and D outcomes appear only when those outcomes are sorted by the result of the joint measurement, the same post-selection described in §8, so no signal passes between them (§6.6).

The no-cloning theorem states that no quantum operation can create an identical copy of an unknown quantum state while leaving the original intact, a theorem that follows directly from the linearity of quantum theory. [67] WEX offers a physical reading of why wave packets cannot be cloned. Copying a wave packet's structure requires first defining its dynamical features, but dynamical features are properties rather than values (§3.1). The only way to define a value is an

independent energy exchange, which defines a single outcome and alters the wave packet in the process. Any attempt to copy without measurement through sub-quantum coupling fares no better as it unifies the original and the blank into a single wave packet rather than producing two independent copies, exactly as the formalisms all predict. An unknown structure can be transferred, as in teleportation, but never duplicated.

12. Ninth Consequence: Quantum Computing Read as Geometric Computing

WEX views quantum algorithms (the software of quantum computers) as manipulating wave packet structure (the hardware of quantum computers) to compute, much like classical software algorithms manipulating transistor gate hardware to compute. This section gives the WEX reading of what quantum algorithms do and adds no new predictions. The difference lies in the hardware. Transistor gates are binary while wave packets have many structural degrees of freedom. N unified wave packets form a single non-separable structure which requires 2^N complex amplitudes to model the range of possible outcomes. Quantum algorithms exploit this structural flexibility by manipulating wave packet geometry through precisely controlled unifying energy exchange, navigating a computational path through a continuum of geometric possibilities. [68]

Each quantum gate operation unifies with the computational packet via sub-quantum coupling, progressively reshaping its structure while maintaining the computational wave packet's unity. The algorithm imposes sequential constraints on the unified packet's physical structure, altering its geometry as it navigates a computational path through the continuum of possible wave packet geometries, incorporating all of the algorithmic constraints in the computational packet's final structure. A subsequent measurement of the final packet reveals a geometrically optimized answer in the particle signature as classical information.

Viewed through WEX, quantum algorithms can be read as executing 'geometric computing' on a unified wave packet, manipulating its geometry through controlled unifying energy exchanges that impose constraints on the unified computational packet. Under WEX, the computational power is understood not as processing multiple superposed states simultaneously, but as manipulating continuous geometric structure in ways discrete bit states cannot access.

13. Tenth Consequence: Universality Across Scale, Formalism, and Geometry

WEX asserts universality along three dimensions: formalism, scale, and geometry. These universality claims follow from its ontology together with the shared features distilled in §2. If wave packets are the only persistent constituents of physical reality, they must form the basis of matter at every scale, so scale independence is entailed by the ontology and not added to it. The same holds for any formalism and geometry that produces the same outcomes of quantum interactions in the time and space dimensions of our physical universe. The remainder of this section reviews the support for each aspect of universality.

Section 2 made the formalism independence argument by showing that eleven formalisms with vastly different mathematical structures and assumptions all predict the same shared properties and behaviors of fundamental quantum scale entities. Each formalism can be viewed as modeling the intrinsic wave behavior of matter advocated by WEX using different abstract mathematical models.

Section 10 made the WEX scale independence argument by showing there is no scale at which physics predicts wave packet dynamics will cease. The evidence of atoms, molecules, condensed

matter structures, biological organisms, and stars exhibiting quantum effects, together with the quantum effects predicted for black holes, is supported by a wide range of sub-disciplines at different scales within physics.

The remaining universality claim is that WEX is independent of geometry. The WEX principle was developed, and its consequences traced within our 3D universe using standard non-relativistic quantum mechanics frameworks for clarity. But WEX's core ontological claim transcends this context as the extension to 4D spacetime using relativistic principles is consistent with WEX as discussed in §3.1, §6.5 and §10. Relativistic quantum theory predicts that whether a detector registers particles depends on the detector's own motion, as when an accelerating detector registers particles in a vacuum where an inertial detector registers none. [69] Under a particle ontology this is puzzling, but under WEX it is expected since particle signatures are records of energy exchange with a detector, not objects that exist independent of one.

The amplituhedron computes particle interactions in a model quantum field theory as the volume of a geometric object that lies beyond 4D spacetime, with locality and unitarity emerging from geometry rather than being assumed. [24] This focus on the importance of geometry echoes WEX's emphasis on wave packet geometry as a dynamical feature and quantum computing as geometric computing. And its treatment of spacetime locality as emerging from a more fundamental geometry is consistent with this paper's openness to structure beneath spacetime (§3.1). Along these same lines the relativistic transactional interpretation's explanation of the Born rule requires a 'substratum' beneath 4D spacetime. [23,31] WEX views these innovative approaches as pushing the boundaries of conventional thinking, an approach that may one day lead to a more fundamental branch of physics operating in higher physical dimensions and/or beneath the Planck scale.

The WEX principle should apply equally whether physically real wave packets are limited to the three space and one time dimensions of our physical universe or extend into higher dimensions or a substratum, provided these extensions continue to represent or predict the same shared formalism features discussed in §2 on which the WEX reading is grounded. Spatiotemporal realism (§1) requires only that wave packets exist in the physical universe we can observe, thus a substratum or higher dimensions in which they also extend are compatible with it.

This universality across scale, formalism, and geometry suggests that WEX identifies something deeper about underlying reality: the relationship between physically real fundamental energy patterns, their structural properties, energy exchange dynamics, and measurement device interactions. The core insight is not technical but ontological: Our physical reality is solely constituted of physically real energy patterns that propagate and exchange energy while particles as conventionally thought of in physics are not fundamental.

14. Conclusion

The paper identified the common features across quantum formalisms and read them ontologically under spatiotemporal realism, arriving at a wave realism ontology. It then precisely defined a number of ambiguous terms in standard quantum theory, encapsulated the result in a two-part claim, and traced its consequences.

> ***The Wave Energy Exchange (WEX) Principle:*** *(i) The sole persistent constituents of physical reality are spatially extended energy waves that can exchange energy with other waves, interfere and/or unify with them, and dynamically evolve in our space and time*

universe. (ii) Particles with precise property values are point-in-time signatures of quanta of energy emitted by an energy wave and absorbed by a measurement device.

Wave packets are physically real energy patterns. Particle signatures are evidence of energy exchange, not physical objects that exist. Wave packet structure is the currency of quantum physics, not hidden variables, not quantum information, not superposed particles. The wave-particle duality perspective should be replaced with the intrinsic wave nature of reality perspective and particle-centric terminology replaced with wave-centric terminology.

The ten consequences traced in this paper illustrate the efficacy and explanatory value of the WEX principle, suggesting that seemingly disparate phenomena can all be understood through a single ontological lens. Open questions remain including the measurement problem (which WEX partially addresses) and why energy is exchanged in quantized amounts (which quantum theory takes as an empirical fact and does not derive). While WEX does not fully resolve these problems, a potentially fruitful path forward involves embracing the intrinsic wave nature of matter and structuring research programs and experiments to further explore this perspective.

More broadly, WEX reframes quantum reality ontologically: Every star, planet, organism, cell, molecule, atom, subatomic particle, and elementary particle consists of physically real, spatially extended, interacting wave energy patterns that are the sole fundamental constituents of physical reality. The WEX reading is consistent with wave packet energy dynamics at all scales and across any formalism or geometry that predicts the same eight shared features. This perspective could help shift quantum foundations from a primarily abstract mathematical discipline toward one grounded in the physical mechanism of energy exchange. It opens research pathways across multiple domains: quantum information theory as structural constraint theory, quantum computing read as geometric computing exploiting wave packet structure, optimizing measurement device design around wave packet structural properties, etc. Embracing the intrinsic wave nature of matter as an ontology can become an organizing principle for better understanding quantum phenomena at all scales of the universe and across all mathematical frameworks.

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