A Stochastic Network Interpretation of Quantum Information

research@foleosoft.com

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I. Introduction

We present a formalism for quantum information that reinterprets the two degrees of freedom in the quantum state as representing an epistemic statistical distribution over the configuration of bits in a quantum computer's memory and an ontic phase network. The phase network is posited as a deterministic, connective property of the system, encoding its internal connections and influencing the stochastic perturbations of the bits during quantum gate operations. Our approach replaces the collapse of the wavefunction with Bayesian inference, describing measurement updates as probabilistic updates to the observer's knowledge, rather than as a physical collapse of the system's state. The phase network, analogous to the parameters of a neural network, evolves according to deterministic rules. The quantum state is reinterpreted as the result of a coordinate transformation from polar to Cartesian coordinates, serving as a computationally convenient encoding of the same information. The Born rule is then understood to be a result of this computationally convenient encoding and not a foundational postulate.

II. The Formalism

A. Splitting the Quantum State

The quantum state is represented by a complex-valued vector ψ. Complex numbers inherently encode two degrees of freedom, which can be analyzed by decomposing the system into two real-valued representations. This approach facilitates a clearer understanding of the physical significance of these degrees of freedom.

To begin, we decompose the quantum state into two real-valued vectors. Since complex numbers are conventionally interpreted as Cartesian coordinates on the complex plane, we can express the quantum state as a pair of real-valued coordinates, as shown in Equations (1) and (2).

$$\vec{x} = \Re(\psi) \tag{1}$$

$$\vec{y} = \Im(\psi) \tag{2}$$

If these vectors are interpreted as Cartesian coordinates, they can be transformed into polar coordinates without losing information about their two degrees of freedom. This transformation yields two new real-valued vectors, as defined in Equations (3) and (4).

$$\vec{p} = \vec{x} \odot \vec{x} + \vec{y} \odot \vec{y} \tag{3}$$

$$\phi = \operatorname{arctan2}(\vec{y}, \vec{x}) \tag{4}$$

The derivation of these vectors in terms of ψ is detailed in Equations (5) and (6).

$$\vec{p} = |\psi|^2 \tag{5}$$

$$\phi = \arg(\psi) \tag{6}$$

We propose that the quantum state should be interpreted as encoding two distinct degrees of freedom: the probability vector (Equation 3) and the phase vector (Equation 4). The probability vector is treated as epistemic, reflecting uncertainty about the system's state. In quantum computing, qubits are merely bits that exist in definite configurations, but the dynamics of quantum circuits are fundamentally stochastic. This limits our ability to track the ontic states of individual bits, instead requiring probabilistic descriptions as given in Equation (3).

The interpretation of the statistical distribution as epistemic uncertainty is valid only in the computational basis. This aligns with the framework of Hooft[1] and Barandes[2] which advocate privileging a specific basis for representation. If we were to interpret the statistical distribution as epistemic uncertainty across all bases simultaneously, it would imply the system has definite bit values for every possible basis. This contradicts the Kochen-Specker theorem,[3] necessitating the selection of a privileged basis.

The phase vector in Equation (4) is interpreted as an ontic property of the system. It does not represent a substantive entity but rather a connective characteristic of the system, as discussed in greater detail later.

B. Update Rules

Consider a probabilistic computer where the memory state is represented by a vector of probabilities. Each logic gate is then described by a stochastic matrix that governs the evolution of this probability vector. The system's update rule is thus given by Equation (7), where Γ denotes the stochastic matrix.

$$\vec{p}' = \Gamma\vec{p} \tag{7}$$

Equation (7) can alternatively be expressed as an element-wise summation, as shown in Equation (8).

$$\vec{p}'_j = \sum_k \Gamma_{jk}\vec{p}_k \tag{8}$$

While this formulation captures the behavior of a probabilistic computer, it is insufficient to describe the probabilistic nature of quantum computation. To extend this framework to quantum systems, we incorporate the phase vector ϕ, which accounts for the system's connective dynamics. This is formalized in Equation (9).

$$\vec{p}_j' = \sum_k \Gamma_{jk}\vec{p}_k + f(\phi) \tag{9}$$

The phase vector ϕ is interpreted as a deterministically evolving property of the system. When the memory bits of a quantum computer undergo stochastic perturbations, the exact nature of these perturbations is influenced by the current state of the phase vector. The mechanism by which this occurs is defined in Equation (10).

$$f(x) = \sum_{k<l} 2\theta\sqrt{\Gamma_{jk}\Gamma_{jl}\vec{p}_k\vec{p}_l} \tag{10}$$
$$\text{where } \theta = \cos(x_k - x_l + \Theta_{jk} - \Theta_{jl})$$

While Γ represents a stochastic matrix, Θ denotes an additional real-valued matrix referred to as the phase matrix. The derivation of these matrices from a unitary operator is detailed in Equations (11) and (12), respectively.

$$\Gamma = |U|^2 \tag{11}$$

$$\Theta = \arg(U) \tag{12}$$

To complete the formalism, we must also define update rules for the phase vector. This representation relies on polar coordinates, where the phase vector encodes angular information. To compute these angles, we require Cartesian coordinates, which are derived from the probability vector and phase vector via the function defined in Equation (13).

$$g(j,\epsilon) = \sum_k \sqrt{\Gamma_{jk}\vec{p}_k}\sin\Big(\phi_k + \Theta_{jk} + \epsilon\Big) \tag{13}$$

Using this function, the update rule for the phase vector is given in Equation (14).

$$\phi_j' = \text{arctan2}\left(g(j,0), g(j,\frac{\pi}{2})\right) \tag{14}$$

Thus, the probability and phase vectors can be updated directly based on the description of quantum logic gates in terms of stochastic and phase matrices, eliminating the need to revert to the orthodox formalism of complex-valued quantum states represented by ψ.

C. Measurement

Consider a quantum algorithm in which the qubits in the quantum computer are not in a known state. The observer possesses only a probability distribution over the ontic states of the memory. Now, suppose the observer measures a single qubit of the quantum computer's memory, but not all of them.

Since the probability vector represents a classical distribution of probabilities, the observer can update it using Bayes' theorem,[4] as formalized in Equation (15).

$$Pr(H_k|E) = \frac{Pr(E|H_k)Pr(H_k)}{Pr(E)} \tag{15}$$

To illustrate, consider a quantum computer with two qubits. After executing a specific quantum circuit, the observer assigns a probability vector to the memory, as shown below.

$$\vec{p} = \begin{pmatrix} 0.1 \\ 0.2 \\ 0.3 \\ 0.4 \end{pmatrix}$$

The number of hypotheses about the memory state equals 2^N, where N is the number of qubits. For N=2, there are 2^2=4 hypotheses: H_{00}, H_{01}, H_{10}, and H_{11}, corresponding to all possible configurations of the memory.

Now, suppose the observer measures the most significant bit and finds it to be in state 1. To compute the probability of this evidence, we use the general definition provided in Equation (16).

$$Pr(E) = \sum_k \left(Pr(E|H_k)Pr(H_k)\right) \tag{16}$$

The prior probability of a hypothesis $Pr(H_k)$ is simply the value assigned to it in the probability vector. The likelihood $Pr(E|H_k)$ is 100% if the evidence E is compatible with H_k, and 0% otherwise, as incompatible evidence cannot occur under that hypothesis.

If the most significant bit is measured to be 1, the updated probabilities are as follows: the first two hypotheses (H_{00}, H_{01}) are incompatible with the evidence and are thus reduced to 0%.

$$Pr(E|H_{00}) = 0$$
$$Pr(E|H_{01}) = 0$$
$$Pr(E|H_{10}) = 1$$
$$Pr(E|H_{11}) = 1$$

With this information, we can apply Bayes' theorem (Equation 15) to compute the updated probability vector, as shown below.

$$\vec{p} = \begin{pmatrix} 0.0000 \\ 0.0000 \\ 0.4286 \\ 0.5714 \end{pmatrix}$$

This process is known as Bayesian inference. As a further example, if the least significant bit is measured and found to be 0, a similar update can be performed, yielding the new probability vector given below.

$$\vec{p} = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix}$$

The key insight of this formulation is that Bayesian inference suffices to account for measurement updates. The phase vector, which evolves deterministically through the system, does not require updating upon measurement due to U(1)-gauge symmetry.[5] Unlike the probability vector, the phase vector does not represent a statistical distribution, and thus Bayes' theorem is not applicable to it.

It is important to emphasize that, in this interpretation, the probability vector is epistemic as it represents the observer's knowledge on the intrinsic properties of the system, in this case the values of the bits in quantum computer. On the other hand, the connective properties, represented by the phase vector, are ontic. Hence, measurement only requires reducing the probability vector, not the phase vector.

D. Information-Sharing Principle

Consider a quantum circuit involving two qubits initialized in the $|00\rangle$ state. A Hadamard operator is applied twice to the most significant qubit. The resulting circuit and its corresponding probability vector are illustrated below. Here, bit vectors denoted by a lower-case B represent real-valued basis vectors corresponding to its subscript.

$$\vec{p} = |(H \otimes I)(H \otimes I)|^2 \vec{b}_{00} = \vec{b}_{00}$$

Now, consider a second quantum circuit where the least significant qubit is not left idle. Instead, the state of the most significant qubit is recorded onto the least significant qubit using the CNOT operator.

$$\vec{p} = |(\mathrm{H} \otimes \mathrm{I})\mathrm{CNOT}(\mathrm{H} \otimes \mathrm{I})|^2 \vec{b}_{00} = 0.5(\vec{b}_{00} + \vec{b}_{11})$$

In the first case, the marginal probabilities for the most significant qubit follow a degenerate distribution, as the repeated Hadamard operations collapse the state to a classical bit. In contrast, the second circuit produces a uniform distribution for the most significant qubit. This difference is significant: the CNOT operator is a passive, non-interacting transformation that merely copies the control qubit's state to the target qubit.

The control qubit (most significant qubit) should remain unaffected by the CNOT operation, yet its marginal probabilities are altered by the introduction of the CNOT gate. This phenomenon, which we term the Information-Sharing Principle (ISP), arises from the correlation established between the two qubits. Even though the CNOT operation is passive in the moment, it creates a dependency between the qubits, which can influence the statistical outcomes of future logic gates. This is a direct consequence of the update rules formalized in Equations (9) and (14).

The ISP underscores a fundamental principle: knowing something about a quantum system's state requires physical interaction. If an observer gains epistemic knowledge of a qubit's state, this knowledge must be encoded through a physical correlation such as an interaction between the qubit and a measuring device. While such a measurement does not immediately alter the qubit's state, it introduces a statistical dependency that can affect future measurements. This aligns with the idea that quantum mechanics inherently links information and physical interactions, even in seemingly passive operations.

E. Transitional Probabilities

In a model where quantum information evolves stochastically, it is possible to define transitional probabilities, the probabilities that the quantum circuit transitions from a definite configuration at time t to another at time t+1. Bell's framework for modeling quantum systems as a flow of probability, akin to a fluid, provides a method to compute these probabilities.[6]

$$Pr(x_{t+1} = b | x_t = a) = ...$$

Equation (17) quantifies the probability current between configurations a and b, representing the flow of probability from a to b. This flow can be formalized as a vector over all unique configurations b.

$$J_{a \to b} = \theta \sqrt{\vec{p}_{t+1}(b) \Gamma_{ba} \vec{p}_t(a)} \qquad \text{where } \theta = \cos\big(\phi_{t+1}(a) - \phi_t(b) + \Theta_{ba}\big) \tag{17}$$

To construct a positive flow vector, Equation (18) removes negative components, resulting in a residual deficit (Equation 19) compared to the initial probability distribution.

$$J^+_{a \to b} = \max(0, J_{a \to b}) \tag{18}$$

$$\Delta_a = \vec{p}_t(a) - \sum_k J^+_{a \to k} \tag{19}$$

The deficit is then redistributed to normalize the flow vector, yielding a normalized flow vector (Equation 21). This normalized vector enables the derivation of conditional probabilities (Equation 22), which describe the likelihood of transitioning from one configuration to another. This formalism establishes a stochastic framework for modeling quantum evolution while preserving the probabilistic structure of the system.

$$\tilde{J}_{a \to b} = \tilde{J}^+_{a \to b} + \Delta_a \cdot \vec{p}_{t+1}(b) \tag{20}$$

$$Pr(x_{t+1} = b | x_t = a) = \frac{\tilde{J}_{a \to b}}{\vec{p}_t(a)} \tag{21}$$

F. Determinism

A deterministic framework can be constructed by introducing a random variable to govern transitions between configurations. By computing the transitional probabilities at each discrete time step and using a random variable to select outcomes, the model retains the structure of stochastic dynamics while introducing a deterministic evolution of the system's definite configuration.

Equation (22) defines the quantum computer's definite configuration in the next step, where the system evolves via a permutation matrix.

$$\vec{s}' = \mathcal{P}\vec{s} \tag{22}$$

If we are utilizing a global random variable λ which acts as a seed for a pseudorandom number generator (PRNG) to generate the value γ as shown in Equation (23). This PRNG must be one that yields a unique value for γ every subsequent time it is utilized. Therefore, the value of γ should evolve deterministically even though it begins with a random configuration. This randomness does not represent fundamental randomness but merely the observer's ignorance of the initial value of λ.

$$\gamma = \text{PRNG}(\lambda) \text{ where } \lambda \sim \mathcal{U}(0,1) \tag{23}$$

We can use γ to select a new configuration from our vector of transition probabilities computed in Equation (21). The next step is to define a cumulative distribution function (CDF) for this probability distribution, as shown in Equation (24). The CDF can then be used to select a new configuration for the system, as shown in Equation (25), using γ.

$$F(x_k) = \sum_{i=1}^{k} Pr'(\mathbf{x}_A)_i \text{ where } F(x_0) = 0 \tag{24}$$

$$\vec{s}' = x_k \iff F(x_{k-1}) \leq \gamma < F(x_k) \tag{25}$$

An intuitive way to conceive of the CDF is an analogy to an analog clock with lines on the clock to separate its face into 2^N different zones. The size of each zone will be proportional to the likelihood of the associated configuration of bits occurring after conditioning on the idle bits. The value λ is the time on the clock and thus determines which zone the clock hand falls into and thus the system's specific configuration of 2^N possible configurations.

This configuration can then be used to construct a new permutation matrix. This matrix will be an identity matrix except for swaps between the new configuration given in Equation (25) and the current configuration. The methodology to construct this permutation matrix is detailed in Equation (26).

$$\mathcal{P} = \mathbf{I} - \vec{s}\vec{s}^{\top} - \vec{s}'\vec{s}'^{\top} + \vec{s}\vec{s}'^{\top} + \vec{s}'\vec{s}^{\top} \tag{26}$$

Finally, this permutation matrix can be used to discretely evolve the bits according to Equation (22). The choice of permutation matrix is deterministic, as it is ultimately determined by λ.

The permutation matrix evolves the system deterministically, as its choice is dictated by λ. However, λ is a global random variable, not localized to individual bits. A model utilizing a localized λ can also be constructed where random variables are associated with individual bits.

It is well-known that universal quantum computation requires only single-qubit gates and the CNOT gate (a permutation matrix).[7] Thus, decomposing a quantum circuit into single-qubit gates and permutation matrices ensures that transitional probabilities are necessary only from single-bit operations, allowing localized random variables to suffice.

III. Discussion

A. Primacy of Our Formalism

If a textbook were to present quantum mechanics using this formalism, where each unitary operator is expressed as a combination of a stochastic matrix and a phase matrix, then, guided by these update rules, it would be possible to evolve the probability vector and phase vector directly. This would eliminate the need to revert to the traditional formalism of quantum mechanics, which relies on the complex-valued quantum state ψ.

Therefore, this formalism should not be viewed as a derivative or secondary representation of the orthodox framework. Instead, it offers a self-contained, independent description of quantum dynamics. It is mathematically equivalent to the orthodox formalism but does not presuppose it. One could equally argue that the orthodox formalism presupposes this one, as the latter provides a foundational interpretation of quantum states, while the former serves as a more convenient mathematical shorthand for calculations.

The precedence of the orthodox formalism historically does not justify its dominance in interpretative ontology. The formalism presented here should instead be granted interpretive primacy, with the orthodox framework regarded as a computational tool that simplifies expressions and calculations.

The probability vector and phase vector emerge from a coordinate transformation from Cartesian to polar coordinates. This transformation does not introduce new elements to the formalism but re-expresses the two inherent degrees of freedom already present in the quantum state ψ. Thus, even within the orthodox formalism, ψ can be interpreted as a simultaneous representation of the probability vector and phase vector, rather than the reverse.

B. The Born Rule

The equivalence between the definition of the probability vector in terms of the quantum state (Equation 5) and the Born rule[8] is of interest. The probability vector is thus guaranteed to always reflect the same statistical outcomes as the squared magnitude of the wave function, rendering the Born rule redundant as an independent postulate.

In our interpretation, the primary mathematical objects are the probability vector and the phase vector. The probability vector is inherently probabilistic, always encoding the statistical distribution of the current configuration of the quantum computer's memory. This ensures that the quantum system's behavior is consistently described by stochastic dynamics, even as the phase vector evolves deterministically as an ontic state of the system.

The Born rule, in this framework, emerges as a coordinate transformation from polar to Cartesian coordinates. This transformation does not introduce new physical content but re-expresses the two degrees of freedom (probability and phase) in a form that simplifies calculations. However, this representation obscures the direct physical meaning of the probability vector and phase vector, as their roles become less explicit in the complex-valued formalism.

The quantum state is not interpreted as a singular, collapsing entity upon measurement. Instead, the bits in the quantum computer's memory are always in a definite configuration, as represented by the probability vector. This configuration undergoes stochastic perturbations, which are influenced by the current state of the phase vector. The phase vector, evolving deterministically, acts as a connective, ontic property of the system, distinct from the epistemic uncertainty captured by the probability vector.

We do not posit any physical collapse of the quantum state upon measurement. Instead, the observer performs a Bayesian inference on the evidence obtained from the measurement. While this process influences the future statistics of the bits in subsequent interactions (via the ISP), it does not alter the system's state at the moment of measurement. The measurement updates the probability vector, reflecting new knowledge about the system's configuration, but the phase vector remains unchanged as a deterministic ontic state.

Thus, the orthodox formalism of quantum mechanics, with its reliance on the complex-valued wave function and the Born rule, is reinterpreted as a computational convenience rather than a foundational truth. The probability vector and phase vector provide a more transparent, physically grounded description of quantum dynamics, where the Born rule is a byproduct of coordinate transformations rather than an independent axiom.

C. The Phase Network

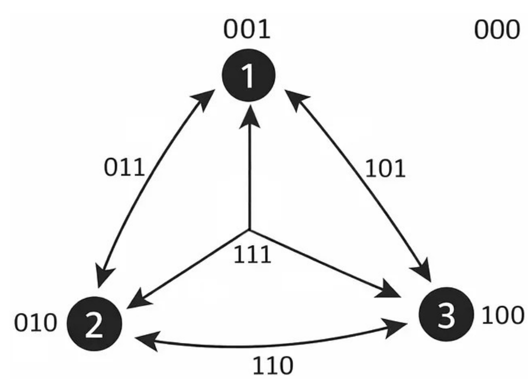
We have argued that the probability vector is epistemic, while the phase vector is ontic. Both vectors are of the same size, as they are both defined over the same configuration space. However, if the phase vector is an ontic state of the system, it cannot be interpreted as a list of possible configurations. Instead, it must be understood as a state of the system itself, rather than a representation of its possible configurations.

At first, this may seem conceptually challenging. A vector that is the same size as a configuration-space vector, such as one that contains 2^N elements for N qubits, does not naturally lend itself to being interpreted as a state of the system. This is because the configuration space of N qubits has 2^N possible states, while the state space of N qubits (i.e., the space of all possible quantum states) is typically described as a 2N-dimensional space. However, in our framework, the phase vector is not a list of possible configurations; it is a state of the system, and as such, it must be interpreted differently from the probability vector.

To clarify, consider the case of three qubits. The configuration space of three qubits has 2^3=8 possible classical states. However, the number of variables needed to describe the state of the system is not 8: it is N = 3, the number of qubits. This raises an important question: how can a vector of size 2^N (like the phase vector) be interpreted as a state of a system with only N degrees of freedom?

The answer lies in interpreting the phase vector not as a list of possible configurations, but as a connective property of the system. Specifically, we conceive of the phase vector as representing a phase network: a structure that encodes connections between the bits in the computer's memory. This is analogous to the structure of an artificial neural network, where nodes, connections, and biases are all represented by parameters.

The first entry of the phase vector (e.g. 000) represents the bias of the network. The entries where only a single bit is 1 (e.g., 001, 010, 100) correspond to nodes in the network. The entries where multiple bits are 1 (e.g., 011, 110, 111) correspond to connections between nodes.



The simultaneous connection between all three nodes is a hyperedge and thus the phase network is a hypergraph. The total number of all edges (including self-loops, which correspond to the nodes, and an empty edge, which corresponds to the bias) of a hypergraph is 2^N.[9]

This structure allows the phase vector to encode a connective state of the system, where the phases represent how the qubits are related to one another. The phase network, therefore, is not a physical entity or substance, but rather a connective property of the system, akin to the structure of a neural network.

In this interpretation, the phase vector is not a list of possible configurations but a state of the system, encoding the connections among its components. This allows it to maintain the same size as the configuration space while still being interpreted as an ontic state of the system. The phase vector's role is not to track configurations but to represent the system's connective structure, which persists independently of the probabilistic uncertainty captured by the probability vector.

The phase network, as a connective property of the system, evolves deterministically throughout the quantum computation. This deterministic evolution stands in contrast to the stochastic behavior of the probability vector, which reflects the observer's epistemic uncertainty about the system's configuration.

While the phase vector changes over time, its evolution follows fixed, deterministic rules, independent of the probabilistic updates that govern the probability vector. Even as the bits' configuration evolves probabilistically, the phase vector's deterministic character remains intact, preserving its role as a foundational, connective property of the system.

D. Interpretation of the Phase Network

In our interpretation, only half of the quantum state corresponds to a physical property of the system, specifically the degree of freedom associated with the phase network. Furthermore, we do not interpret this network as an entity, a substance, or an object, but rather as a method for describing and visualizing connections between the bits in the system. This is a property of the system's state, not an object with autonomous existence outside of the bits.

It is possible to design an experiment in which two different observers assign different values to the phase network, reminiscent of Wigner's thought experiment.[10] A common solution to this is to propose the existence of an absolute quantum state of the universe, known as the universal wavefunction.[11] If this approach were applied to our interpretation, there would exist an absolute state of the phase network between all bits. The different states described in practical experiments by different observers would then be apparent rather than absolute.

However, the introduction of the universal wavefunction is an additional postulate that lacks independent mathematical justification or derivation from the structure of quantum information. Therefore, the inclusion of such a concept is questionable.

A more parsimonious approach would be to treat the phase connections as a contextual property of the system. This property physically varies between measurement contexts, analogous to how the velocity of an object can genuinely change and be measured differently in distinct contexts.

Indeed, this aligns our interpretation with aspects of quantum contextual realism.[12] Different conscious observers may describe the same system with varying values for its phase network, not because they are conscious observers, but because they occupy distinct measurement contexts.

Similarly to quantum contextual realism, we can interpret measurement as more than a revelation of knowledge; it also represents a shift into a new physical context.[13] This is because knowledge requires specific physical conditions of knowing. Therefore, gaining knowledge about something previously unknowable implies the establishment of a new physical context. Thus, the acquisition of knowledge is not merely a passive revelation of the system's state but analogous to transitioning to a different reference frame.

Previously, we used the ISP to explain why observations of a system's state, despite being passive, cause the system to evolve differently in subsequent interactions. This explanation requires adopting a third-person perspective, which may not always be available.

With this approach, one can also explain why the system evolves differently in subsequent measurements after a measurement is made without the ISP. By treating this as a shift to a new context, the laws of physics must adapt to this new physical context. While our approach is compatible with both contextual and non-contextual interpretations, a contextual approach is more parsimonious and does not require an additional postulate akin to the universal wavefunction.

E. Locality

It is clear that the phase network is not a localized property of the system. Quantum bits of information can be stored within physical particles that are separated from one another in space, yet they can still maintain a phase connection. This phase relation can influence the statistical outcomes of their measurements. Therefore, this interpretation is intrinsically non-local.

We interpret the lesson of Bell's theorem[14] not as a reason to reject the existence of objective reality, but as a discovery that the natural world is genuinely non-local. A similar perspective has been proposed by Rizzi,[15] emphasizing that the correct interpretation of Bell's theorem is to embrace non-locality.

A common concern is that non-locality conflicts with special relativity, but this is not necessarily the case. When Einstein introduced special relativity in 1905, his predictions aligned with Lorentz's earlier 1904 theory,[16] though Einstein's framework eliminated the need for a preferred spacetime slicing.

This historical precedent demonstrates that introducing a preferred slicing does not inherently contradict special relativity. Such a slicing becomes relevant in deterministic models of quantum mechanics, where it is necessary to reconcile trackable ontic states with Lorentz invariance.

Our model, however, is stochastic and does not track ontic states explicitly. This avoids empirical contradictions with special relativity while retaining non-locality at the level of the ontic states. The model's predictions for measurement readouts remain Lorentz invariant, ensuring compatibility with special relativity at the observable level.

Two distinct layers of objective reality emerge in this framework: (1) Measurement readouts; directly observed outcomes, which are consistent with special relativity, and (2) ontic states; observable yet not always observed non-local configurations of the system.

While the first layer adheres to Lorentz invariance, the second does not require explicit modeling to maintain compatibility with empirical evidence. The stochastic nature of our model further avoids the need for a preferred slicing, as ontic states are not trackable and their evolution is not deterministic.

This dual-layer structure resolves potential tensions with special relativity: non-locality operates in the unobserved dynamics, while measurement outcomes preserve relativity's empirical constraints. Even if ontic states were trackable and deterministic, introducing a preferred slicing to reconcile their evolution with special relativity would not contradict empirical predictions.[17]

Thus, quantum mechanics can be interpreted as relativistic in the context of measurement readouts while allowing non-local dynamics beyond direct observation. This framework avoids contradictions by distinguishing between what is observed and what underlies those observations.

F. Occam's Razor

The rejection of Occam's Razor as a justification for denying the existence of ontic states when a system is unobserved is central to this framework. While these ontic states are not explicitly tracked in the model, they remain counterfactually observable. An observer could, in principle, perform alternative measurements to reveal properties of the system. If a system possesses properties that are observable under counterfactual conditions, those properties must exist in some form, even when unmeasured. This aligns with the principle of object permanence, a foundational tenet of philosophical realism.

Consider a classical universe governed by stochastic dynamics: such a system would still require a probabilistic model (e.g., an evolving vector of probabilities) to describe its behavior. Occam's Razor could not be used to deny the existence of ontic states in such a context, as their counterfactual observability persists. This argument is equally valid in classical and quantum mechanics. Notably, quantum mechanics does not necessitate the conclusion that ontic states vanish when unobserved. Their existence is supported by the fact that they are observable via counterfactual measurements, even if their stochastic dynamics preclude tracking within the model.

Representing planetary orbits as circles (a simpler geometric form) initially appears more parsimonious than using ellipses. However, this simplicity necessitates the introduction of epicycles to reconcile observations, ultimately increasing ontological complexity. Similarly, assuming particles lose observable properties when unobserved may seem simpler in terms of assumptions, but it requires introducing collapse postulates or Many-Worlds interpretations to resolve inconsistencies, inflating ontological complexity.

This analogy underscores the core argument: denying the existence of ontic states does not resolve complexity, it merely shifts it. The stochastic nature of quantum mechanics explains why these states are not tracked in the model, not that they do not exist. Counterfactual observability and object permanence remain consistent with empirical evidence, even in the absence of explicit tracking.

Thus, the rejection of Occam's Razor in this context is not only tenable but necessary to avoid compounding ontological complexity.

G. Future Research

We believe that it is possible to prove that Equation (8) becomes a good approximation for Equation (9) in macroscopic systems when marginalized over the environment. This would be equivalent to decoherence as reformulated in this formalism. The influence of the additional non-linear term $f(\phi)$, and thus the relevance of the phase vector ϕ, would become less crucial to making correct statistical predictions on a macroscopic scale, and thus could, in many cases, be safely ignored.

However, we have not yet formalized this in this formalism and are leaving it to future research.

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