# The Prototime Interpretation of Quantum Mechanics[1]
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Abstract

*We propose the Prototime Interpretation of quantum mechanics, which claims that quantum entanglement occurs in a "prototemporal" realm which underlies spacetime. We claim that the Prototime Interpretation (PI) is worthy of further consideration as a superior explanation for perplexing quantum phenomena such as delayed choice, superposition, the wave-particle duality and nonlocality. In Section One, we introduce the Prototime Interpretation. Section Two identifies its advantages. Section Three discusses several implications of the view, such as its deterministic nature and relation to the simulation hypothesis.*

At the heart of contemporary physics is a contradiction between the study of the very big and the very small — between the supermassive structures (e.g., black holes) in Einstein's theory of general relativity and the subatomic arena of quantum mechanics. Work in the field of quantum gravity (QG) tries to resolve this contradiction, and increasingly, it is claiming something astonishing: the fundamental ingredients of reality are not spatiotemporal. Instead, spacetime emerges from something more fundamental, something defined in terms of a mathematical structure that dispenses with any spatiotemporal metric.[2] Just as the transparency of water is not found in a single $H_2O$ molecule, at the finest level of resolution, spacetime drops out of the picture.

[1] We are grateful to Misha Klopukh, Michael Ostroff, Edwin Turner, Dean Rickles, George Musser and Michael Huemer for feedback on this paper.

[2] George Musser, *Spooky Action at a Distance: The Phenomenon That Reimagines Space and Time--and What It Means for Black Holes, the Big Bang, and Theories of Everything*, First edition (New York: Scientific American/Farrar, Straus and Giroux, 2015); Nathan Seiberg, "Emergent Spacetime," in *The Quantum Structure of Space and Time*, 2007, 163–213, https://doi.org/10.1142/9789812706768_0005; Brian Swingle, "Spacetime from Entanglement," *Annual Review of Condensed Matter Physics* 9, no. 1 (March 10, 2018): 345–58,

Herein, we sketch and explore a position in which spacetime emerges from a quasi-temporal reality called "prototime." According to this position, there is time in the sense of spacetime, as well as a different, more fundamental, "prototemporal" dimension or parameter from which spacetime emerges. (Some may instead wish to think of this dimension simply as a 'parameter,' instead of a dimension, because they regard dimensions as spatiotemporal entities.) Our paper is tentative and exploratory. The argument form is inference to the best explanation. We claim that the Prototime Interpretation (PI) is worthy of further consideration as a superior explanation for perplexing quantum phenomena such as delayed choice, superposition, the wave-particle duality and nonlocality.[3,4] In Section One, we introduce the Prototime Interpretation. Section Two identifies its advantages. Section Three discusses several implications of the view, such as its deterministic nature.[5]

## I. The Prototime Interpretation (PI)

Our point of departure is the simple fact that a quantum system that is entangled in a "pure state" has zero Von Neumann entropy when the system is considered as a whole, where Von Neumann entropy is a common measure of the entropy of quantum systems.[6] (A quantum system, S, is in a "pure state" when it is in a precise, well-defined state, being described by a single wave function that contains all the information about S.) We further appeal to the following uncontroversial point:

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https://doi.org/10.1146/annurev-conmatphys-033117-054219; Christian Wüthrich, Baptiste Le Bihan, and Nick Huggett, eds., *Philosophy Beyond Spacetime: Implications from Quantum Gravity*, 1st ed. (Oxford University Press, 2021), https://doi.org/10.1093/oso/9780198844143.001.0001.

[3] For an earlier framing of the Prototime Interpretation and implications for consciousness and the self see Schneider, "Emergent Spacetime, the Megastructure Problem, and the Metaphysics of the Self," *Philosophy, East and West*, Vol. 74, Nu 2. She has previously stressed that the very same entities that fundamental physics investigates, these entities that spacetime emerges from, may very well be the very same ingredients that give rise to consciousness (Schneider, Susan. "Idealism, or Something Near Enough." In Idealism: New Essays in Metaphysics, edited by Tyron Goldschmidt and Kenneth L. Pearce, Oxford University Press, 2017. pp. 234-256).

[4] Susan Schneider, "Emergent Spacetime, the Megastructure Problem, and the Metaphysics of the Self," *Philosophy East and West* 74 (2024): 314–32, https://api.semanticscholar.org/CorpusID:269395209; Susan Schneider, "Idealism, or Something Near Enough," in *Idealism: New Essays in Metaphysics*, ed. Tyron Goldschmidt and Kenneth L. Pearce (Oxford University Press, 2017), 0, https://doi.org/10.1093/oso/9780198746973.003.0017.

[5] In a related target paper for a forthcoming *Journal of Consciousness Studies* special Issue, we employ the prototime interpretation to develop a new version of panpsychism, which we call "Superpsychism." (Schneider and Bailey, forthcoming.) According to Superpsychism, the fundamental physical level has a more advanced form of consciousness than spacetime occupants, in the sense that it exhibits maximal coherence, zero entropy and holistic integration of conscious states. The position differs from Cosmopsychism, for whereas cosmospychists like Goff (2017) and Nagasawa and Wager (2020) locate the fundamental unit of consciousness in the very biggest element, we claim the greatest form of consciousness inheres in the holistically entangled structure, a structure that is not even spatiotemporal and which underlies spacetime itself.

[6] Individual subsystems of an entangled system have non-zero Von Neumann entropy but a system *as a whole* in a pure state (whether entangled or not) has zero Von Neumann entropy, reflecting a state with maximum knowledge/no uncertainty.

1. ***Entanglement connectivity.*** Fundamental particles can be entangled, even across vast spatial distances. When two particles, a and b, are entangled, their properties become correlated such that the state of one particle is instantaneously linked to the state of the other.

This is the "spooky action at a distance," that Einstein referred to, and, bizarre as it is, it has been demonstrated in numerous experiments. Entanglement connectivity is a detectable phenomenon within our universe. It is neither spatiotemporally nor causally isolated from the 4D world. It is not happening in some unrelated, inaccessible, parallel universe but from a part of our universe that we do not yet understand.

Now consider a very controversial claim. For the purpose of argument we suppose, *controversially*, that entanglement connectivity is a causal phenomenon:

2. ***Assumption*****: Entanglement connectivity is causal.** An entangled state, a, either directly causes a change in a particle b, or, the states of a and b are jointly caused by, or mediated by, one or more other state(s) at the prototemporal level.

As Hume observed, empirical investigation of any phenomenon does not actually detect a cause, it merely detects a correlation because causation is not something that can be seen directly in the world, it is only inferred.[7] But normally, a causal relation is an obvious avenue to consider given the presence of a reliable correlation. For saying that there is merely a correlation, rather than a causal relation, calls for explanation as well. And indeed, the idea that entanglement connectivity is a mere correlation is bizarre. However, while it is bizarre to merely assert a correlation, there is an important consideration in its favor, for, of course, the presence of a causal relation between entangled states at vast distances would contradict relativity theory, involving superluminal signaling.[8] For this reason, assumption (2) is very controversial, to say the least.

Notice, however, (2) can be true if it does not lead to spooky action at a distance. More specifically, we propose:

3. **5D-ism.** The universe has at least one added dimension (or parameter) — one in which entanglement connectivity happens. This is not an extended spatial dimension but a parameter of prototemporal connectivity.

According to 5D-ism, the classical, everyday reality we experience exists on the 4D "surface" of a larger 5D universe. The universe has at least five dimensions: three spatial, one temporal, and at least one added parameter or degree of freedom that is nonspatiotemporal, underlying entanglement connectivity. If assumption (2) is correct, this supposed causal connection is not a phenomenon that makes sense merely on the assumption of 4D spacetime, the initial conditions, and the relativistic laws. Indeed, it is quite puzzling from a relativistic framework, as noted. We propose that it may require at least one added parameter, or degree of freedom, that is neither

[7] David Hume, *An Enquiry Concerning Human Understanding*, Dover Philosophical Classics (Mineola, N.Y: Dover Publications, 2004); David Hume, David Fate Norton, and Mary J. Norton, *A Treatise of Human Nature: A Critical Edition*, The Clarendon Edition of the Works of David Hume 1–2 (Oxford: Oxford University press, 2011).

[8] A. Einstein, B. Podolsky, and N. Rosen, "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?," *Physical Review* 47, no. 10 (May 15, 1935): 777–80, https://doi.org/10.1103/PhysRev.47.777.

spatial nor temporal — at least where ‘temporal’ is used in the “Einsteinian spacetime” sense. (Herein, for uniformity we use “temporal” and “time” in the sense of Einsteinian spacetime.) Of course, the standard view is that quantum entanglement involves instantaneous correlations, but due to the No-Signaling Principle, it doesn't allow for faster than light transmission of information. It is not possible to use quantum entanglement to send messages superluminally. However, this does not preclude causation in prototime, for entities in prototime are not ones in which the constraints of spacetime apply. Although the standard picture merely asserts that there is a correlation between entangled states, there is nothing to rule out the possibility that at the level of prototime, there is a causal relation between entangled particles, or the particles’ states are jointly caused by, or mediated by, other state(s) in prototime. *However, macroscopic observers cannot use quantum entanglement to send messages faster than the speed of light, as per the No Signaling Principle.*

How does time emerge from a more fundamental prototemporal reality? Physicists and philosophers have long puzzled over the problem of time’s arrow, the puzzle of why time moves forward, not backwards, given that physical laws seem symmetrical. A popular response to the problem of time’s arrow involves appealing to the phenomenon of entropy.[9] In thermodynamics, entropy is the measure of the disorder in a system. According to the second law of thermodynamics, the total entropy of an isolated system will inevitably increase over time. This means that systems will naturally evolve from ordered states to more disordered states.

This common approach to time’s arrow is particularly suggestive in light of the phenomenon of entanglement. For entangled systems in a pure state — *systems with zero von Neumann entropy and that have not decohered and interacted with the environment — may not really be in spacetime at all.* This is because measurement (with decoherence) introduces entropy, and time’s arrow, into the system. An entangled quantum system that is in a pure state would not be one in which time’s arrow applies. It is only through the process of decoherence that the particles become integrated with spacetime itself. Another way to put the point is that during measurement (with decoherence) the environment ‘measures’ the system and this disturbs it, causing the system to lose its superposition. Doing this introduces thermodynamic entropy into the system and the system transitions to a classical state. An entangled system in a pure state is not in spacetime, but the act of measurement (with decoherence) introduces classical entropy and time’s arrow into the system.

While this point is speculative, there is a body of work lending insight into how time’s arrow emerges that is compatible with our approach (Carol, 2010). Quantum Darwinism (QD) is a well-respected hypothesis that explains the emergence of classical reality from quantum possibilities. In brief, (QD) is dependent on the interaction of (quantum) superpositions that

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[9] Giulia Rubino, Gonzalo Manzano, and Časlav Brukner, “Quantum Superposition of Thermodynamic Evolutions with Opposing Time’s Arrows,” *Communications Physics* 4, no. 1 (November 26, 2021): 251, https://doi.org/10.1038/s42005-021-00759-1; Seth Lloyd, “Pure State Quantum Statistical Mechanics and Black Holes” (arXiv, July 1, 2013), http://arxiv.org/abs/1307.0378; Wojciech Hubert Zurek, “Quantum Darwinism,” *Nature Physics* 5, no. 3 (March 2009): 181–88, https://doi.org/10.1038/nphys1202.

ultimately converge to some stable (classical) state. Some states are more stable than others states, these more stable states are known as "pointer states." For example, a measurement might be a pointer state, which causes the measured particle to decohere to a stable, measured state. All quantum objects interact in this same manner, becoming entangled with each other as they interact, ultimately converging to stable, classical states through the process of decoherence.[10] Because the number of decohered states that is available to any quantum object greatly exceeds the number of available "pure" unentangled quantum states, in practice, classical objects don't interact and suddenly enter into a quantum state. In this manner, (QD) ultimately gives rise to classical temporal ordering. In sum, from quantum decoherence, entropy and time's arrow ultimately emerge from an aspatial, prototemporal arena.

So, according to this view, the phenomenon of quantum entanglement plays a crucial role in our understanding of time's arrow. While classical views link the progression of time to the dispersal of energy and increasing entropy, the modern understanding of Quantum Darwinism sees quantum entanglement as the driving force.[11] As particles become more and more entangled, systems move toward equilibrium, which gives the appearance of time moving in a specific direction. This quantum perspective not only offers a more fundamental explanation for the arrow of time, it also helps bridge the gap between classical and quantum thermodynamics.

Recent experiments have found some support for Quantum Darwinism. For example, two teams, one at Sapienza University of Rome and another from the University of Science and Technology of China, employed photons to simulate quantum systems and their environments. They noted that even a single photon can serve to act as an environment, introducing decoherence and selection, and that the information about the quantum system saturates quickly as more and more of the environment is considered. Further, another experiment (led by Fedor Jelezko at Ulm University in Germany) used a nitrogen atom in a diamond's crystal lattice as the quantum system. The atom's unpaired electron can interact with surrounding carbon atoms. The findings confirmed that the state of the nitrogen atom is "recorded" in its surroundings multiple times, which is consistent with QD's predictions. While these experiments align with QD, they don't conclusively prove QD is the only explanation for the emergence of classicality. However, these tests are still significant steps in understanding the bridge between the quantum and classical worlds.[12]

In sum, ours could be a universe with two time-like dimensions, one that involves time in the familiar sense of spacetime and in which time has a direction or arrow, and a different prototemporal dimension that lacks a direction or arrow. This fifth dimension or parameter is a non-spatial arena, yet prototime involves causation between events. Because time possesses a

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[10] Noah Linden et al., "Quantum Mechanical Evolution towards Thermal Equilibrium," *Physical Review E* 79, no. 6 (June 4, 2009): 061103, https://doi.org/10.1103/PhysRevE.79.061103.

[11] W. H. Zurek, "Environment-Induced Superselection Rules," *Physical Review D* 26, no. 8 (October 15, 1982): 1862–80, https://doi.org/10.1103/PhysRevD.26.1862; Zurek, "Quantum Darwinism"; Ming-Cheng Chen et al., "Emergence of Classical Objectivity of Quantum Darwinism in a Photonic Quantum Simulator" (arXiv, August 5, 2019), http://arxiv.org/abs/1808.07388.

[12] Chen et al., "Emergence of Classical Objectivity of Quantum Darwinism in a Photonic Quantum Simulator."

definite direction upon decoherence, positing a timeless or prototemporal arena in this context does not introduce time paradoxes. This position is novel, and unusual, but we believe it is worthy of consideration, for it takes seriously the possibility that entanglement relations confer an added dimension to reality, one that causally determines events in the 4D world.

## II. Advantages

So, what reason do we have to take this view seriously? It is important to note that the existing explanations of quantum phenomena are difficult to adjudicate. Unfortunately, key claims still remain untestable and/or rely on controversial philosophical assumptions, such as with the many-world interpretation's appeal to branching parallel universes. The Prototime Interpretation faces these same hurdles, and it awaits more formalism. To its credit, it draws from leading trends in physics, such as spacetime emergence and Quantum Darwinism. We further believe the Prototime Interpretation (PI) is worthy of further consideration as a superior explanation for the following well-confirmed yet bizarre phenomena that we now outline. Further, where other theories offer explanations that are equally satisfying, this view may be more parsimonious than leading contenders, such as string-theoretic views of quantum phenomena that require commitments to entities like branes and several extra spatial dimensions.

We propose that the Prototime Interpretation offers the following advantages:

1. (***PI) provides a richer understanding of superposition.*** Quantum superposition is a puzzling phenomenon in which a particle doesn't exist in a single state but exists as a superposed combination of all possibilities, until measurement or observation, at which point the particle has a determinate state. The prototemporal dimension introduces a fundamental timeless level in which the particle is effectively "everywhere, all at once." That is, according to the Prototime Interpretation, the particle does not need to be in a determinate state because there is no singular moment in time, at the prototemporal level, in which it must occupy a determinate state. For time's arrow is not in play. Instead, the particle is in a superposition of all states until a measurement is performed and the particle interacts with the familiar, time-bound universe. This interaction situates the particle in time, forcing it to adopt a definite state.

2. ***PI provides a unique perspective on the No Signaling Principle.*** The standard view says that quantum entanglement involves instantaneous correlations only; due to the No Signaling Principle it does not allow for faster than light transmission of information. Quantum entanglement cannot send messages to macroscopic observers superluminally. We uphold the No Signaling Principle. But notice that "speed of light" is a spatiotemporal notion, requiring both a distance and time metric, both of which are not present at the level of prototime. The phenomenon of time's arrow arises only when systems interact with the environment. Although the standard view must assert that there is merely a correlation between entangled states, to avoid violating the no signaling

> principle, there is actually nothing to rule out the possibility that at the level of prototime, there is a causal relationship between entangled states, (perhaps mediated by something else at that level), not just correlations. However, macroscopic observers cannot use quantum entanglement to send messages faster than the speed of light.

3. *PI rejects "spooky action at a distance."* Related to (2) above is the concern that entanglement seemingly involves instantaneous correlations across vast distances, which seems like superluminal communication or what Einstein famously called "spooky action at a distance" (Einstein, 1935). Because (PI) proposes a non-spatiotemporal arena in which entanglement communication might occur, the instantaneous correlations do not violate the luminal speed limit. Further, no distance metric exists in prototime, for it is aspatial, and so there is no "distance" over which spooky action could occur.

4. The *Wave-particle duality*. Particles are known for exhibiting both wave-like and particle-like features, depending on how they are measured. This phenomenon is an expected feature of the Prototime Interpretation because particles exist fundamentally in a cloud of potential states at the prototemporal level. Only through interacting with the 4D world do they exhibit particle-like (spatial and temporal) behaviors, a duality that is a manifestation of a particle's existence in two different time-like structures.

5. *The double-slit experiment*. The double slit experiment involves particles passing through two slits, generating an interference pattern on a screen. When one attempts to measure which slit the particle travelled through, bizarrely, the pattern of interference goes away, as if the particle somehow decided to behave in a particle-like manner, and not a wavelike manner, based on the fact that it was measured. The Prototime Interpretation says that this bizarre behavior is actually expected, because all possible paths exist until the point of measurement and decoherence. At that point, the particle goes into a determinate state in spacetime.

6. ***Delayed choice phenomena.*** The double-slit experiment discussed above can be modified to become a delayed choice experiment in which the choice of whether to measure the path of the particle is made *after* the particle passes through the slits and yet *before* the particle hits the screen. Astonishingly, the outcome on the screen seems to depend on the choice that is made after the particle passed through the slits, seeming like the particle "decides" how is should behave based on an event that has not yet occurred.[13,14] PI says that the 'choice' made upon measurement is actually an outcome of being in the prototemporal state until a measurement is made.

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[13] "The 'Past' and the 'Delayed-Choice' Double-Slit Experiment," which has been reproduced in A. R. Marlow's "Mathematical Foundations of Quantum Theory" (Princeton University Press, 1984)).

[14] John Von Neumann, Robert T. Beyer, and Nicholas A. Wheeler, *Mathematical Foundations of Quantum Mechanics*, New edition (Princeton: Princeton University Press, 2018).

Now let us turn to an important objection to our claim that PI offers an explanatory advantage with respect to the above phenomena. One can object that these same advantages could be provided by the more straightforward, familiar position that takes spacetime to emerge from an entirely timeless, aspatial reality, rather than from prototime, an idea which, the objector will point out, is unclear. What is the notion of 'quasi-time,' after all?

We will call this more common position the "Timeless Reality" view. Even setting aside the issue of parsimony, which arises for string theoretic versions of the view, we believe the Timeless Reality position is flawed. (Explaining the flaw will also help us flesh out the notion of prototime a bit more). The problem with the timeless Reality view is that it is difficult to see how a fundamental timeless level can yield the universe we experience. All around us is the phenomenon of change—we introspect changes in our conscious states, and both our inner experience and scientific work on consciousness provides details on how objects and properties in the world change and evolve. In contrast to this, the literature on ES often appeals to highly mathematical views of reality, and this can lead to a sort of mathematical Platonism gone mad, where the entire universe is seen as an abstract entity, like an equation.[15] Schneider has elsewhere expressed concerns with this approach because it does not explain how there is a concrete, empirical world in which change occurs (Schneider 2017 a,b). Here, the natural question to ask of this sort of view is: what are mathematical entities? The field of philosophy of mathematics studies this question, and there are longstanding controversies about the nature of mathematical properties. If one is a Platonist it is not clear how abstract mathematical entities can causally interact with the physical world, for a purely aspatial and atemporal reality lacks any kind of concreteness, seemingly casting its lot with a metaphysics disconnected from the concrete, causal world. If one has in mind some form of nominalism about mathematical entities, however, then one needs to explain how they are defining their nominalism; it cannot be in terms of spacetime or macroscopic phenomena like human classificatory systems, on pain of circularity. For entities like spacetime, minds, and classificatory systems, are all presumably ultimately determined by the base level, not the other way around.

Because prototime is not time in the familiar sense of spacetime, in which time has an arrow, it is unsurprising that prototime is hard for humans to grasp. But there are resources in the field of contemporary analytic metaphysics that can help. To begin with, a metaphysical picture of base reality needs some fundamental elements that go beyond abstracta. There must be something in one's fundamental ontology that makes sense of causation and change. Notice that the fundamental level that the PI posits is not one without causal relations. Again, entanglement connectivity is real, and this phenomenon cannot be explained by information transfer *within* spacetime itself. If (2) is correct there is entanglement causation that exists in a different, additional, dimension or parameter that is not just ordinary spacetime. A purely atemporal picture would not seem robust enough to accommodate this underlying causal phenomena, as far as we can tell.

[15] Max Tegmark, *Our Mathematical Universe: My Quest for the Ultimate Nature of Reality*, First edition (New York: Alfred A. Knopf, 2014).

Some philosophers, such as Barry Loewer and David Lewis, contend that fundamental physical reality consists in a spatiotemporal mosaic of properties that are essentially non-dispositional, ("categorical" or sometimes "categorical" properties). Laws of nature and causal relations are merely patterns that supervene on this more fundamental mosaic.[16] While these views were not developed in the context of debates about spacetime emergence, this same neo-Humean "categorialist" view of property natures remains influential. According to this neo-Humean ontology, causation and change supervene upon an underlying acausal, non-dispositional reality. As important and influential as this line of thinking is, however, this kind of ontology, especially when paired with highly mathematical views of fundamental reality, would not provide the needed explanation of how change could exist.[17]

In contrast to this Neo-Humean position, it has been observed that empirical properties seem to be dispositional: properties in nature have some causative effect on something else. We commonly talk about, and identify, properties in terms of what they do— by how those properties impact us, other objects, and our measurement instruments. For example, the notion of electron charge is meaningless without some force or field acting on that charge. If the charge did not interact with anything else, its existence would be, at a bare minimum, permanently epistemically unavailable to us. Further, we could postulate an infinite number of properties that have no causal powers – properties that don't actually do anything at all. However, this would be unparsimonious. Therefore, it seems reasonable to assume that empirical properties have at least partly causal natures. [18,19]

Similar discussions have appeared in the philosophy of science literature. Ontic structural realism (OSR), postulated by James Ladyman and Don Ross, is a view that treats the notion of structure as being primitive, where information transfer through structured interactions mediate causation. In this view, reality is fundamentally nothing but patterns all the way down.[20] This raises a similar issue: that the laws merely articulate structures, and at the fundamental level, they are highly mathematical. But what do the laws relate? That is, what underlying entities are we describing with our highly mathematical physical theories? A common objection to OSR is the mistaken assumption that it views the world as purely mathematical, which would be incongruent with physicalism and any distinction between the concrete and the abstract. The response is that the relational structures are, in fact, real (properties or something else). While they can be mapped to isomorphic mathematical abstracta, that doesn't negate the existence of a physical structure to which they map. PM Ainswoth puts forth an interpretation of OSR where properties and relations

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[16] Barry Loewer and University of Arkansas Press, "Humean Supervenience:," *Philosophical Topics* 24, no. 1 (1996): 101–27, https://doi.org/10.5840/philtopics199624112.

[17] Schneider, "Idealism, or Something Near Enough"; Susan Schneider, "Does the Mathematical Nature of Physics Undermine Physicalism ?," 2017, https://api.semanticscholar.org/CorpusID:9687678.

[18] For an accessible and engaging discussion of these issues see Heil, John. The Universe As We Find It. Oxford University Press, 2012. ISBN 9780199596201.

[19] John Heil, *The Universe as We Find It* (Oxford: Clarendon Press, 2012).

[20] James Ladyman et al., *Every Thing Must Go: Metaphysics Naturalized* (Oxford ; New York: Oxford University Press, 2007).

are ontologically primitive, but objects are not.[21] In the following section we raise a similar approach, one that appeals to bundle theory.

Thus far, we have discussed several explanatory advantages to PI. Because PI does not invoke extra spatial dimensions, and because spacetime emerges from a base reality consisting in prototemporal dispositional properties, we believe the position is parsimonious. Further, in contrast to the Timeless Reality view, which may explain the above quantum phenomena (e.g., superposition) and in some versions, may stand to be equally parsimonious, (invoking the same number of spatial dimensions as PI), PI is better able to explain change, claiming that reality consists in causally interacting prototemporal properties. These are dispositional properties that are defined as being capable of giving rise to spatiotemporal phenomenon. This helps flesh out prototime, illustrating why it is a sort of "quasi-time" that has dynamic features. It is not time in the sense of spacetime, yet it is nevertheless a causal arena, having events that are instantiations of dispositional properties indexed to a prototemporal (and nonspatiotemporal) metric. Now let us explore the metaphysical framework in more detail.

## III. Determinism, Digital Physics, and The Simulation Hypothesis

The Prototime Interpretation is deterministic. Recall our assumption, for the purpose of argument that:

2. **Entanglement connectivity is causal.** An entangled state, a, either directly causes a change in a particle b, or, the states of a and b are jointly caused by, or mediated by, one or more other state(s) at the prototemporal level.

Hidden variable theories claim that the probabilistic nature of quantum mechanics stems from a hidden variable that we have yet to uncover, and that quantum systems are actually deterministic.[22] Consider the behavior of any two entangled states; such are commonly observed to follow a pattern that seems deterministic. For example, measuring one instantaneously impacts the other. Further, the value of one particle is non-randomly correlated with, and indeed, on our view, in some sort of causal relation with, the state of its entangled particle. These facts, when combined with the above assumption and the view that spacetime emerges from entanglement, suggest that the Prototime Interpretation is deterministic. Quantum events are the output of the deterministic function conforming to the probabilistic predictions of standard quantum mechanics.

A natural question is whether one can derive the standard probabilities of quantum mechanics from the underlying prototemporal structure—a deterministic function from states of an entangles system, S, to states in spacetime. Since we cannot access future states in the 4D manifold, it is impossible to access the complete details of the deterministic structure of the universe. To make matters worse, the universe consists in a complex web of entangled states bearing connectivity R

[21] Peter Mark Ainsworth, "What Is Ontic Structural Realism," *Studies in History and Philosophy of Modern Physics* 41 (2010): 50–57, https://api.semanticscholar.org/CorpusID:119776505.

[22] David Bohm and Basil James Hiley, *The Undivided Universe: An Ontological Interpretation of Quantum Theory* (London New York: Routledge, 1993).

to each other, so the "entanglement object" is one singular, enormously complex, entanglement object that underlies all of spacetime. (We shall call this "The Megaobject".) Yet from the vantage point of a hypothetical omniscient being having upon the Megaobject, a larger pattern may be evident, upon considering that past, present and future states of entangled particles. From our vantage point, however, massive intractability looms.

Yet many body experiments have cleverly isolated more complex quantum systems, even entangling a tardigrade.[23] But the question is: what future states are relevant? An obvious candidate is measurement. Here, delayed choice cases may be instructive, for if our theory is correct, the future choice, together with past and present states of the system, provides the hidden variable that maps to outcomes in our spacetime. The choice made in the future is in the elements of the prototemporal structure and it does match the outcome we observe. This explains why the particle seems to "know" the future measurement setting.

There are other exciting implications of determinism as well. For it is possible that spacetime and its occupants are epiphenomenal aspects of the prototemporal level; just as philosophers have entertained that consciousness is itself epiphenomenal, being determined by, and supervenient on, more basic physical properties but itself causally inert, so too, the locus of causal action may be at the prototemporal level, and the 4D world, including our own consciousness, are merely epiphenomenal features of it. This is a major departure from our current worldview, and much of physics, which takes spacetime as the primary arena for causal action.

Now let us turn to a related matter. Thus far, our discussion envisions a universe in which all of spacetime emerges from the quantum decoherence of entanglement objects at the more basic level. Given this, it is natural to ask: is reality itself effectively a quantum computer? Further, might we be in some sort of simulation? While we cannot delve into this matter in detail, we believe this matter calls attention to the need for a richer metaphysical understanding of quantum phenomena.

Digital physics, the intriguing concept suggesting that the universe is, or at least operates like, a computer program, is of interest to many in light of the simulation hypothesis, artificial life, the import of information theory, and more. The core proposition of digital physics, that all phenomena can ultimately be described by information processing or computational rules, together with Nick Bostrom's simulation argument, raises important questions about whether the aforementioned "base level" is that of a computer simulation and whether we might even be faced with an epistemic situation in which we cannot determine, as subjects residing in spacetime, whether a certain approach to EG is right, as opposed to a simulation hypothesis — a sort of underdetermination of theory by all the available evidence.

Indeed, we might appeal to computer simulations to explore the space of theories, to try to resolve the issue, where actual experiments are unavailable. However, perhaps there is no possible function that we could derive that maps the base computation to certain emergent subroutines. Being in a simulation, we may be limited in our ability to build a computer capable of universal computation to the same fidelity as the computational universe in which it exists. It would be like

[23] K. S. Lee et al., "Entanglement between Superconducting Qubits and a Tardigrade," *New Journal of Physics* 24, no. 12 (December 1, 2022): 123024, https://doi.org/10.1088/1367-2630/aca81f.

trying to build a simulated computer that more powerful than the computer running the actual simulation. Interestingly, a machine cannot compute itself in more than real time, according to Stephen Wolfram's principle of Computational Irreducibility.[24] Otherwise, infinite computational speed would be possible. Furthermore, some processes are not inherently mappable to their outcomes using deterministic functions. For instance, the emergence of markets in an economy is dependent on the local interactions of the market participants; however, this relationship can't be compressed to a deterministic mathematical relationship – it requires stochastic simulation or direct observation to derive any insight. This is what we refer to as *algorithmic incompressibility*. It is possible that this is simply an epistemic issue, due to our ignorance of the math and physics required to fully describe this type of system; or it could be of metaphysical origin, representing a fundamental limit to our ability to deterministically compute certain phenomena. If computational irreducibility holds and algorithmic incompressibility has an epistemic limit, the computational speed limit of the 4D Universe might be one that is set by a base reality computing at a finite speed – perhaps suggestive of a simulated reality.[25]

It is worth noting that a process ontology is compatible with a simulation hypothesis because the program can be implemented by properties having their causal powers essentially. On our view, the causal powers of the properties are determined by the role the properties play with respect to the other properties they are entangled with, where the state of one property is instantaneously connected to the state of another, regardless of the "distance" between them in the prototemporal realm. This is a mechanism for property interaction in absence of a normal time dimension. Some in contemporary metaphysics may prefer to claim that base reality 'realizes' macroscopic events, rather than causing them directly. However, if the 4D world is in a computer simulation generated by the base reality then it may be more appropriate to claim that the base reality causes events in the 4D world (what we might call this "upward causation"). This upward causation from the base to the spatiotemporal would be a form of genuine emergence, one without downward causation, perhaps, but one in which the base level causes, rather than realizes higher-level events.

## Conclusion

The protototime interpretation draws from the idea that spacetime emerges from entanglement, which is causally connected through a nonspatiotemporal parameter, called "prototime." We have claimed that time's arrow emerges from entropy arising during quantum decoherence. We have urged that the prototime view deserves consideration as a framework that may address a range of perplexing phenomena in quantum mechanics, such as superposition, delayed choice and spooky action at a distance. It offers a deterministic perspective that suggests the probabilistic nature of quantum mechanics is due to our limited epistemic access to the prototemporal arena.

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[24] Stephen Wolfram, *A New Kind of Science* (Champaign (Ill.): Wolfram, 2002).

[25] Herein, we have been referring to a "base" level for the purpose of discussion, but it is important to bear in mind that for all we know, there is yet a more basic level, and indeed, it is conceptually possible that it is turtles all the way down.

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