Article

Physics Needs a Physical Theory of Observation

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Abstract

The ubiquitous assumption that "systems" can be taken as "given" is wrong. Viewing observation physically as entanglement allows this assumption to be dropped. In the framework that results, initial conditions play no role, time is emergent, observers are ubiquitous, and both "systems" and the theories that describe them are purely model-theoretic entities.

Keywords: Decoherence, Emergence, Entanglement, Model theory

1 Introduction

Which of our basic physical assumptions are wrong? Two that are central to our representation of experimental observations: the assumption that observers manipulate particular, known degrees of freedom when they "prepare" physical systems, and the assumption that they obtain outcome values that specify the states of these same, known degrees of freedom when they perform measurements. One might have thought that Moore's 1956 theorem showing that even classical systems cannot be uniquely identified by finite observations [1], Bell's 1964 theorem - and the subsequent experimental results - showing that entanglement across macroscopic distances must be taken seriously [2], Kochen and Specker's 1967 theorem showing that observational outcomes depend on observational context [3] and Wooters and Zurek's 1982 theorem showing that pure states cannot be copied [4] would have shaken our faith in these assumptions. They have not: the assumption that arbitrary quantum states described by arbitrary bases can be prepared is implicit in the practice of specifying such states as the starting points of calculations, while the assumption that experimental outcomes encode the states of specified degrees of freedom is implicit in the representation of observables - e.g. positive operator-valued measures (POVMs) - as defined over explicitly-specified Hilbert spaces.

Three points are argued here. The first is that neither observations nor decoherence calculations can specify the boundary in Hilbert space that encloses all and only the degrees of freedom being manipulated or observed at any particular instant; hence if such boundaries are assumed, they must be regarded, as they are in classical physics, simply as "given." Hilbert space boundaries are not, however, actually given: they are actually unknown and unknowable. Treating such boundaries as "given" distorts physical theory: it renders our perspective special, turns the universe into a multiverse and makes time

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appear objective. The second point argued is that a physical representation of observation that makes no *a priori* assumptions about the allocation of degrees of freedom to particular systems can be constructed. The third is that constructing such a physical representation of observation is theoretically productive. It forces us, in particular, to ask what observables, outcomes, and classical records of outcomes are, and it suggests answers to these questions that depend only on the notions of Hilbert-space decomposition and entanglement. It suggests a physically-realist picture of the world in which initial conditions play no role, time is emergent, observers are ubiquitous, "anthropic" arguments are pointless, and physical theories are model-theoretic representations of families of Hilbert-space automorphisms. *Useful* physical theories, in this conceptualization, correspond to representations that can be generated by classically-feasible algorithms; such theories therefore correspond to the structures for reality allowed by Tegmark's Computable Universe Hypothesis [5].

2 Observations without systems

Classical physics straightforwardly assumes that "systems of interest" are simply *given* to observers. Schlosshauer, for example, puts this assumption as follows:

> "Here (i.e. in classical physics) we can enlarge our 'catalog' of physical properties of the system (and therefore specify its state more completely) by performing an arbitrary number of measurements of identical physical quantities, in any given order. Moreover, many independent observers may carry out such measurements (and agree on the results) without running into any risk of disturbing the state of the system, even though they may have been initially completely ignorant of this state."
>
> ([6] p. 16)

Not only are "many independent observers" assumed to be able to identify and carry out measurements on the *same* system, they are assumed to be able to do this when "completely ignorant" of the system's state. To be completely ignorant of the state of a system is to not know the values of any of its state variables: to not know its location, direction or rate of motion, mass, size, shape, or anything else about it. How do such ignorant observers distinguish the system they are to observe from its environment? The implicit assumption is clearly that they don't have to: the identity of the system is simply given.

This assumption that systems are simply given to observers is carried over into both realist and instrumentalist approaches to quantum theory. For example, Ollivier, Poulin and Zurek define an emergent sense of "objectivity" within the environment as witness formulation of decoherence theory as follows:

> "A property of a physical system is *objective* when it is:

1. simultaneously accessible to many observers,

2. who are able to find out what it is without prior knowledge about the system of interest, and

3. who can arrive at a consensus about it without prior agreement."

([7] p. 1)

The requirement that observers can "find out" properties of a physical system even though they have no "prior knowledge" or "prior agreement" about the system is equivalent to the classical requirement that observers can be "completely ignorant" of a system's state but still distinguish it from its environment. As in the classical case, this amounts to the assumption that the system is simply given to each observer [8, 9]; the assumption that the observers communicate, moreover, requires that each of the other observers be simply given to each observer. On the opposite end of the interpretative spectrum, in Fuchs' formulation of quantum Bayesianism "the real world is taken for granted" ([10] p. 7) with "every particular that is and every way of carving up every particular that is" (p. 22) counting as a "system" with which observers can interact by deploying the appropriate POVMs. This seemingly classical ontology is rendered quantum by requiring that each of these systems has a fixed "dimension" represented formally by its Hilbert-space dimension. This addition is significant: observers are now given not just systems, but Hilbert space representations. The question of how, in practice, observers distinguish the degrees of freedom and hence the Hilbert spaces they are interacting with from their surrounding environments is never discussed [11].

A more subtle form of the assumption that systems are "given" to observers underlies the idea that observers can be considered to be "outside of" the systems they are observing. Tegmark gives this classical idea a contemporary form as the "External Reality Hypothesis (ERH)": the claim that "there exists an external physical reality completely independent of us humans" ([5] p. 101). As an external reality "completely independent" of the *physical* states of any observers actually capable of conducting observations would violate energy conservation, the ERH appears to require that the epistemic states of human observers, including in particular the states encoding their knowledge of system boundaries, are independent of their physical states. Where then do such epistemic states come from? They must be "given" by some means that is logically prior to physics.

The problem with the idea that systems are "given" to observers is that it is plainly false. If systems are described by Hilbert spaces, to be given a system is to be given its Hilbert space, or alternatively, to be given the boundary in the Hilbert space $\mathcal{H}_{\mathbf{U}}$ "of everything" that picks out the particular degrees of freedom - the particular positions, momenta, spins, baryon numbers, and so forth - that are currently being manipulated or observed. No one is born knowing the boundaries in $\mathcal{H}_{\mathbf{U}}$ that mark off the degrees of freedom of ordinary objects, let alone the degrees of freedom of their first laptop computer or of Alpha Centaurii. Lower bounds on the collections of degrees of freedom being manipulated or observed can be obtained from experiments, but Moore's theorem [1] and similar results within automata theory show that upper bounds cannot, even in the case of experiments on classical finite-state machines. Hence the identities of "systems" as Hilbert-space boundaries cannot be learned inductively. Boundaries in $\mathcal{H}_{\mathbf{U}}$ cannot, moreover, be calculated using decoherence theory: one cannot trace over the "environment" surrounding the degrees of freedom being manipulated or observed without knowing which degrees of freedom those are. Even if spontaneous local collapses of components of $|\mathbf{U}\rangle$ or objective superselection by some objective, observer-independent environment are assumed to somehow "prefer" certain collections of degrees of freedom, no finite amount of local experimental observations is sufficient to determine the boundaries of such preferred collections [8, 9]. Hence assuming that observers know the Hilbert-space boundaries of the collections of degrees of freedom being observed in the very definition of observation, as is being assumed when a POVM is defined over a particular, explicitly-specified Hilbert (sub)space, is assuming that observers have knowledge that they cannot possibly obtain.

It is useful to state the limitation on observers' knowledge of system boundaries being argued for here in the conceptually-fundamental language of "experience" employed by Fuchs [10]. When an observer deploys a POVM to investigate the world, what results is an action of the world on the observer, one that is "experienced" as an outcome, a value that fills a slot in some data structure. To assume that the observer knows, in advance, what degrees of freedom will be observed when the POVM is deployed is to assume that the observer knows, in advance, how the world works: only by knowing how it works can the degrees of freedom that the world will recruit to cause a future experience be known. Some such knowledge can be obtained by observation; one can establish empirical *lower limits* on the complexity or creativity of the world's response to any given deployment of a POVM. Establishing the upper limits required to claim knowledge of Hilbert-space boundaries, however, would require an ability to observe the whole world in action, an ability no observer can claim.

It is also worth noting that this limitation on the knowledge of observers is fully independent of whether observers are assumed to have "free will" or act autonomously. An observer may well *intend* to manipulate only specific degrees of freedom, or intend to observe only specific degrees of freedom, and may act freely on these intentions. What is ruled out is the implicit assumption that the intentions of observers are deterministically binding on the world: what is ruled out is the idea that an observer can define a POVM as acting only on some Hilbert subspace $\mathcal{H}_{\xi}$, and by this bit of mathematics guarantee that the outcomes obtained when that POVM is implemented and deployed will depend, as a matter of *physical* fact, only on $|\xi\rangle$. This assumption that observers can choose which degrees of freedom the world will recruit to cause their next experience goes well beyond free will: it is an assumption of omnipotence.

If the assumption that observers know the boundaries in $\mathcal{H}_{\mathbf{U}}$ that mark off the degrees of freedom that are being manipulated or observed in any particular instance is abandoned, the formal representations of experimental manipulations and observations must be modified to no longer require it. The simplest such modification is to redefine all POVMs as acting on $\mathcal{H}_{\mathbf{U}}$ as a whole [8]. With this redefinition, observers are regarded as querying the entire universe with the one or more distinct POVMs at their disposal, and as identifying as "systems" *whatever* combinations of degrees of freedom their POVMs detect. This way of defining systems is, of course, familiar: it is how "particles" are defined by particle detectors, how functional modules are defined by software engineers, and how "black boxes" are characterized by reverse-engineering principles. A physics that takes the human epistemic predicament seriously is a physics that treats *everything* as a black box, regardless of how well it has thus far been characterized. This is not an assumption of "autonomy" in the sense of Fuchs [10] or William James; it simply reflects ignorance in principle of the degrees of freedom that any particular black box might turn out to have. As will be seen, a deterministic universe - a universe governed by a Schrödinger equation - in which the boundaries of "systems" can never be pinned down has all the characteristics of a multiverse without actually being one.

3 Decoherence without decoherence

To say that observers deploy POVMs defined over $\mathcal{H}_{\mathbf{U}}$ and record their outcomes is a formal description of observation but is clearly not a physical theory: what an "observer" is and how such a thing could "record" an outcome are left unspecified. Let us assume, then, that an observer $\mathbf{O}$ is a collection of degrees of freedom within $\mathcal{H}_{\mathbf{U}}$, full stop: *any* collection of degrees of freedom, without exception, can be regarded as an observer. Let us also assume that $\mathbf{U}$ evolves under the action of some unitary propagator $e^{-(i/\hbar)H_{\mathbf{U}}(t)}$. For simplicity, suppose that the outcome values returned by a POVM $\{E_i^{\xi}\}$ depend, as a matter of fact, only on the state of some degree of freedom ξ in $\mathcal{H}_{\mathbf{U}}$. In order for $\mathbf{O}$ to record a classical outcome k_j of an action of $\{E_i^{\xi}\}$ on $\mathcal{H}_{\mathbf{U}}$ at some time t_j, the state $|\mathbf{O}(t)\rangle$ of $\mathbf{O}$ must be and remain classically correlated, again as a matter of fact, with $|\xi(t)\rangle$ for some finite interval Δt. Quantum theory provides only one way for this to be the case: there must exist a degree of freedom ϕ within $\mathbf{O}$ such that a measurement of $|\phi(t)\rangle$ determines the outcome of a measurement of $|\xi(t)\rangle$ and vice-versa for $t_j \leq t \leq t_j + \Delta t$. At least between t_j and $t_j + \Delta t$, in other words, $|\phi\rangle$ and $|\xi\rangle$ must be monogamously entangled.

Under what conditions can a pair of monogamously entangled states $|\phi\rangle$ and $|\xi\rangle$, where $|\phi\rangle$ is within some stipulated component of some tensor-product decomposition of $\mathcal{H}_{\mathbf{U}}$ and $|\xi\rangle$ is arbitrary, be found? Harshman and Ranade, for example, have recently shown that if $\mathcal{H}_{\mathbf{U}}$ has finite dimension, a decomposition $\mathcal{H}_{\mathbf{U}} = \phi \otimes \xi \otimes \mathcal{H}_{\mathbf{R}}$ can be finitely constructed in which $|\phi \otimes \xi\rangle$ is maximally entangled and $\mathcal{H}_{\mathbf{R}}$ is a residual "everything else" [12]; the conditions under which such a decomposition can be finitely constructed for an infinite-dimensional $\mathcal{H}_{\mathbf{U}}$ remain unknown. Hence the answer, up to the issue of finite construction, is that such an entangled pair can *always* be found. This result has an intuitive classical analog: if an ensemble of randomly oriented, randomly-evolving spins, for example, is made large enough, the probability of finding two spins that remain classically correlated for a finite interval Δt can be made arbitrarily close to one. In the limit of an infinite ensemble, the probability becomes one; as Tegmark puts it, an exact duplicate of you sharing your entire experiential history exists in some alternative concordance-model universe [13]. *Any* degree of freedom ϕ within an observer $\mathbf{O}$ can, therefore, be regarded as encoding a classical record of the state of *some* other degree of freedom ξ within $\mathcal{H}_{\mathbf{U}}$. The catch, in an infinite universe, is that $\mathbf{O}$ has no way of determining to what degree of freedom the classical record refers. For $\mathbf{O}$, the degree of freedom ξ is simply *whatever* the POVM $\{E_i^{\xi}\}$ detects. As noted above, this is the predicament of any observer in a theory that does not assume that knowledge of the degrees of freedom of observed systems is given *a priori*.

From the perspective of a state $|\phi\rangle$ that encodes classical information about its monoga mously-entangled partner $|\xi\rangle$, the residual "everything else" $\mathbf{R}$ is the environment. This environment does not, however, dissipate the coherence between $|\phi\rangle$ and $|\xi\rangle$; it effectively amplifies it. The decoherence time - the Δt over which the classical correlation survives - is a measure of the "naturalness" of the decomposition $\phi \otimes \xi \otimes \mathcal{H}_{\mathbf{R}}$ in the face of $e^{-(i/\hbar)H_{\mathbf{U}}(t)}$, i.e. a measure of the extent to which a local symmetry $e^{-(i/\hbar)H_{\mathbf{U}}(t)}|\mathbf{R}\rangle|_N \sim |\mathbf{R}\rangle|_N$ exists in some neighborhood N of $|\phi \otimes \xi\rangle$. A locally-unchanging environment effectively "isolates" $|\phi \otimes \xi\rangle$ and hence amplifies its coherence, but such isolation can fail at any moment. An ion trap, for example, can provide a local neighborhood of $\mathbf{R}$ that amplifies coherence between degrees of freedom trapped inside, but this amplifying decomposition is delicate, and will quickly collapse if the next time step of $e^{-(i/\hbar)H_{\mathbf{U}}(t)}$ introduces an experimenter twisting a knob, a leak in the vacuum system or a laboratory-wide power failure.

The delicacy of classical correlations implemented by quantum entanglement renders the stability of classical records paradoxical: how can a classical record, such as a set bit in a computer's memory, be regarded as classically correlated for a macroscopic time with a past event? Classical computer science answers this paradox: a set bit is meaningless - it is not classically correlated with anything - in the absence of a global interpretation of the hardware of which the bit is a component not only as a computer, but as a computer implementing a particular virtual machine with a particular history of inputs and hence a particular execution trace. Such interpretation requires a *current* observation, and hence the deployment of a POVM that accesses the *present* state of whatever degrees of freedom implement the memory. The output of this memory-accessing POVM must comprise a data structure that supports linked lists of self-describing outcome values such as '$|\xi\rangle = k_j$ at t_j' or more compactly, (ξ, k_j, t_j). An observer $\mathbf{O}$ can be considered to be equipped with a classical memory Ψ from which previous observational results are accessible only if that observer is equipped with a POVM $\{E_i^{\mathbf{\Psi}}\}$, defined like all other POVMs over $\mathcal{H}_{\mathbf{U}}$, that yields linked lists of outcome records such as the above that are dependent, as a matter of fact, on the physical state $|\Psi\rangle$ of the degrees of freedom that implement the memory. Like any observer equipped with any POVM, $\mathbf{O}$ cannot be regarded as knowing *which* degrees of freedom encode any particular retrievable record; $\mathbf{O}$ can only be regarded as regarding whatever is retrieved as a remembered record, a record that *says* 'k_j is classically correlated with $|\xi\rangle$'.

Nothing is assumed in the above about the kinds of degrees of freedom that compose the observer $\mathbf{O}$ or how these degrees of freedom are distributed in $\mathcal{H}_{\mathbf{U}}$; all that is required is that $\mathbf{O}$ comprise a sufficient number of degrees of freedom to have resources available for both entanglement with external systems and classical record keeping. The POVMs deployed by $\mathbf{O}$ are determined solely by the entanglement relations that are permitted to survive by the propagator $e^{-(i/\hbar)H_{\mathbf{U}}(t)}$. Hence a consequence of the current representation of observation is that all sufficiently large neighborhoods in $\mathcal{H}_{\mathbf{U}}$ in which the local propagator is not a constant can be considered to contain observers, some of which are able to produce and some of which are able to both produce and re-access classical memories of past events. Our universe can, therefore, be considered to be full of observers that bear no resemblance to us other than being composed of physical degrees of freedom and subject to entanglement; the "cognitive" capabilities of these observers depend solely their representational and computational power [8]. The decompositions and entanglement relations that define those observers will, in general, be nothing like those that define us; their "anthropic arguments" will concern observations of "systems" that are, in general, nothing like ours. This "pan-observerist" position is familiar from classical computer science, which considers any sufficiently large collection of degrees of freedom that executes some non-trivial dynamics to be a computer executing some algorithm or other.

4 Observation as semantics

The foregoing suggests a purely-relational, purely model-theoretic formal representation of observation. If $\mathcal{H}_{\mathbf{U}}$ is a Hilbert space, the set of all possible actions by unitary propagators is the set $\mathcal{A}(\mathcal{H}_{\mathbf{U}})$ of automorphisms of $\mathcal{H}_{\mathbf{U}}$. All automorphisms except the Identity support the existence of observers, so all automorphisms except the Identity are observable. This basic restriction makes sense: to make an observation is to *do something*, which requires a non-trivial propagator. An automorphism A that results in a state $|\mathcal{H}_{\mathbf{U}}\rangle$ that can be decomposed as $|\mathcal{H}_{\mathbf{U}}\rangle = |\mathbf{O} \otimes \mathbf{S}\rangle \otimes |\mathbf{R}\rangle$ for collections of degrees of freedom $\mathbf{O}$, $\mathbf{S}$ and $\mathbf{R}$ can be considered an "observation" by $\mathbf{O}$ via a POVM $\{E_i^{\mathbf{S}}\}$ that produces an outcome $k_j^{\mathbf{S}}$ dependent on the state $|\mathbf{S}\rangle$ of some "system" $\mathbf{S}$. This "observation" is strictly relative to $\mathbf{R}$, and the decoherence times of its records depend on the behavior of $e^{-(i/\hbar)H_{\mathbf{U}}(t)}$ in $\mathbf{R}$. In general many such $\mathbf{O} \otimes \mathbf{S} \otimes \mathbf{R}$ decompositions will be possible; hence any given A corresponds to many observations by distinct observers in distinct environments that record distinct outcomes referring to distinct "systems."

From a model-theoretic perspective, the symbol '$\mathbf{S}$' in the outcome record $k_j^{\mathbf{S}}$ is just a logical constant, a name; it refers to whatever the POVM $\{E_i^{\mathbf{S}}\}$ detects. A set $\{k_j^{\mathbf{S}}\}$ of outcomes generated by $\{E_i^{\mathbf{S}}\}$ can be thought of as a set $\{k_j^{\mathbf{S}}\}$ of automorphisms on an abstract and otherwise-structureless "object" $\mathbf{S}$. It is natural to interpret a dual representation of these automorphisms as "states" of $\mathbf{S}$. As observations with $\{E_i^{\mathbf{S}}\}$ correspond to automorphisms of $\mathcal{H}_{\mathbf{U}}$, it is equally natural to regard a sequential pair of observations $(k_j^{\mathbf{S}}, t_j), (k_l^{\mathbf{S}}, t_l)$ as a "state transition" implemented by some automorphism A_{jl} acting on $\mathcal{H}_{\mathbf{U}}$, i.e. as implemented by $e^{-(i/\hbar)H_{\mathbf{U}}(t)}$.

As noted above, a classical record of a previous observation is an outcome of a memory-accessing POVM $\{E_i^{\mathbf{\Psi}}\}$ that depends on the physical state of some collection of degrees of freedom Ψ. An action of $\{E_i^{\mathbf{\Psi}}\}$ on $\mathcal{H}_{\mathbf{U}}$ produces a linked list of classical "records," for example $(\xi, k_1, t_1)...(\xi, k_N, t_N)$. The symbol '$\xi$' is again, from a model-theoretic perspective, simply a name; the symbols 'k_N' and 't_k' are finite strings. If 'ξ' is identified with the "object" $\mathbf{S}$ and 'k_j' with its "state" k_j, it is natural to represent such a linked list as a history $k_1^{\mathbf{S}} \rightarrow k_2^{\mathbf{S}} \rightarrow ... \rightarrow k_N^{\mathbf{S}}$ of $\mathbf{S}$ parameterized by a linear "coordinate" t. The A_{jl} then serve as propagators as above. Because each history corresponds to the action of a POVM, consistency conditions can be imposed in the standard way.

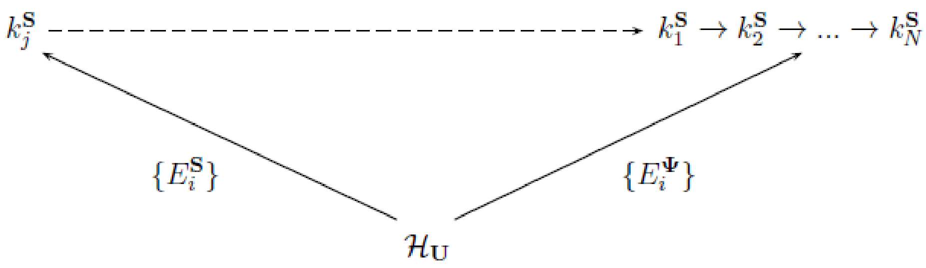

Fig. 1: Model-theoretic construction of states (left) and histories (right) by POVMs $\{E_i^{\mathbf{S}}\}$ and $\{E_i^{\Psi}\}$ acting on $\mathcal{H}_{\mathbf{U}}$. Physically, each POVM is an automorphism of $\mathcal{H}_{\mathbf{U}}$ The "system" and "memory" collections of degrees of freedom $\mathbf{S}$ *and* $\mathbf{\Psi}$ *have no stated bounds in $\mathcal{H}_{\mathbf{U}}$. The dashed line indicates a frame problem solution by* $\mathbf{O}$.

Associating a current observation k_j^{ξ} of $|\xi\rangle$ and a current observation $k_1^{\mathbf{S}} \to k_2^{\mathbf{S}} \to ... \to k_N^{\mathbf{S}}$ of a "memory" Ψ clearly requires that $\mathbf{O}$ be capable of *identifying* ξ with the remembered $\mathbf{S}$. Whether to identify some observed ξ with some remembered $\mathbf{S}$ is a special case of the well-known "frame problem" in artificial intelligence, the special case in which what must be updated following an action - the observation - is the identities of the systems involved. A frame problem solution is effectively a *theory* of identity preservation across time. Consonant with the principled ignorance of observers regarding degrees of freedom, the frame problem has only heuristic solutions; in the case of human observers, these require simulation of possible histories by the pre-motor planning system [14]. Any frame-problem solution is, moreover, strictly observer-relative; one cannot say that an observer has a "theory" or implements a "mechanism" without a decomposition of $\mathbf{U}$ that stipulates what degrees of freedom comprise the observer.

Subject to the assumption of a frame problem solution by the observer, the current representation of observation reproduces the familiar "many worlds" conception of quantum theory with one exception: "worlds" are replaced by discrete physical operations that access collections of degrees of freedom interpretable as memories. Operating on a memory produces a representation of a classical history, but this representation refers, physically, to the *current* state $|\mathbf{U}\rangle$. The "time" parameter is completely internal to such representations; all observations physically occur "now." The standard representation of "branching" as a divergence from a shared past into equally-real futures has no meaning in this framework: there is no objective past, so there is nothing for alternative futures to diverge from. "Histories" are decoherent only in the sense of being defined by different memory-access operations; there is no sense in which alternative histories can be regarded as "environments" of each other. Histories, moreover, refer to "systems" only as abstractions structured solely by the recorded state transitions; there is no sense in which alternative histories can be said to refer physically to any "system" other than $\mathbf{U}$ itself. There is, therefore, no "multiverse" in either the concordance-model sense of distinct classical histories driven by distinct initial conditions or the more purely quantum-theoretic sense of distinct "branches" evolving through a common objective time.

5 Conclusion

Ever since Heraclitus (ca. 500 BCE), researchers who have asked "what is observation?" have concluded that observers cannot *know* what they are observing, and hence cannot *know* what they are manipulating. Moore [1] and others formalized this fundamental "no-go" result in classical automata theory. The standard formalism with which physical manipulations and observations are represented nonetheless assumes that the particular collections of physical degrees of freedom being manipulated or observed can simply be taken as given. This holdover from classical physics distorts physical theory by treating Hilbert space as containing regions with physically-meaningful boundaries that are respected by physical processes, in particular by decoherence.

It has been shown here that if observation is treated as a physical process, the assumption of "given" systems can be dispensed with. Treating observation physically requires addressing the questions of what observers, classical records and memories are. Quantum theory and classical computer science jointly answer these questions: observation is entanglement plus semantics, and memories are simply states of the universe. The fragility of entanglement is dealt with by acknowledging it: all observations, including observations of degrees of freedom that implement memories, occur "now." Time in this framework is purely emergent: "initial conditions" play no role. There is a physical universe containing physical degrees of freedom, but no physical multiverse, and no branching of histories. All "objects" and their "states" are pure, model-theoretic abstractions.

A *physical theory* in this framework is a description of a set of data that has lower algorithmic complexity than an explicit listing of the data themselves. A useful theory is a classically-feasible algorithm. Probabilities, and mathematical expressions in general, appear in the current framework only as components of theories. Any theory must, first and foremost, incorporate an ontology in the form of a solution to the frame problem: an observer-implemented heuristic that identifies "systems" across observations. How theories are physically implemented by collections of degrees of freedom that constituite observers, and hence how they physically enable predictions and adaptive behavior, is an open question, one of the most interesting in all of science.

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