Classical selection and quantum Darwinism

The quantum Darwinism approach offered by Wojciech Zurek (PHYSICS TODAY, October 2014, page 44) is based on a quantum "credo" embedded in the usual mathematical postulates of quantum mechanics: A quantum state is a vector in a Hilbert space, it undergoes a unitary evolution, and composite systems are described by tensor products that allow entangled states. In what may be a hint at something else, Zurek adds a repeatability postulate stating that an immediately repeated measurement yields the same outcome. He justifies the postulate with the argument that "classical repeatability is a given: Measurements reveal classical states, so repeatability follows from their objective existence. . . . Repeatability is key for the very idea of a state as a predictive tool: The simplest prediction is that a state is what it is." Then Zurek's goal is to deduce the usual next "postulates" of quantum mechanics, the so-called collapse postulate and Born's rule.

In our opinion, the main trouble with his (quite respectable) attempt is that it starts from a purely mathematical credo: Vectors in a Hilbert space come directly from the sky, and you must believe in them to reach enlightenment. That approach may not be the best to reach physical conclusions, and before one speaks about vectors in a Hilbert space, some physics may be required to specify what the "state" really is.

As we have discussed in our work,[1,2] such a "quantum state without mathematics," which we call a modality, has a very specific feature: It does not belong to a system, as it would in classical physics, but jointly to the system and to its context—the arrangement of experimental equipment that gives access to the system. And in a given context, such a modality is indeed certain and repeatable—that is, it is real and objective. Perhaps that is what Zurek actually means when he writes, "A state is what it is." We offer a simple example: A photon does not "have" a polarization at 45°, but it will be transmitted with certainty (a property of the system) through a polarizer oriented at 45° (a property of the context).

Such thinking will not invalidate Zurek's arguments, but it will turn them on their heads: The credo actually already contains the conclusion he wants to reach—that the experiments must be defined classically; without that, a quantum state has no meaning.[2] Therefore, the PHYSICS TODAY article does not explain, as Zurek says, "why we experience our world as classical." Rather, it shows—remarkably—that quantum mechanics is a consistent theory.

References

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2. A. Auffèves, P. Grangier, http://arxiv.org/abs/1409.2120.

Alexia Auffèves
Institut Néel
Grenoble, France
Philippe Grangier
(philippe.grangier@u-psud.fr)
Institut d'Optique
Palaiseau, France

This short letter in response to Wojciech Zurek's article "Quantum Darwinism, classical reality, and the randomness of quantum jumps" points out extant rebuttals in the literature to some of the author's key claims.

On the first page of his arXiv.org version of the PHYSICS TODAY article (http://arxiv.org/abs/1412.5206), Zurek states that

> decoherence selects preferred pointer states that survive interaction with the environment. They are localized and effectively classical. They persist while their superpositions decohere. Decoherence marks the border between quantum and classical, alleviating concern about flagrant . . . manifestations of quantumness in the macroscopic domain.
>
> Here we consider emergence of "the classical" starting at a more fundamental pre-decoherence level, tracing the origin of preferred pointer states.

However, the idea that preferred pointer states naturally "emerge" from the quantum level has been refuted in the literature, in particular in a paper[1] showing that "classical" pointer states do not emerge unless a key aspect of classicality has been tacitly assumed from the beginning. In other words, the "quantum Darwinism" program is fatally circular.

The assumption generating the circularity usually takes the form of a predesignated system that is considered separable from its environment (the same assumption appears in the discussion about information flow in Zurek's article). The system acquires decohered observable (or stable) states because it is presumed to be distinguishable from a designated set of environmental subsystems, all assumed as having random phases—with respect to each other and the system. The only correlations between the system and the environmental subsystems are assumed to be established via the designated Hamiltonians.

However, in the absence of this sort of predesignated partitioning of all degrees of freedom into the system and its surroundings—measurement apparatus, environment, and so forth—where the initial phase of each subsystem is random, the desired decoherence and emergence of pointer states, or einselection, do not follow. The partitioning is inevitably based on what a human observer would be able to identify and measure, such as distinguishable atoms and molecules, so the account is dependent on assuming the classical realm of the observer.

The need for this pre-partitioning fatally conflicts with the claim that classicality emerges naturally from the quantum realm: Absent a pre-partitioning of all degrees of freedom into uncorrelated systems of interest, classical pointer states do not emerge. With unitary-only dynamics (lacking nonunitary collapse), the quantum realm does not have any *a priori* preference for the assumed uncorrelated degrees of freedom. On the contrary, a unitary-only evolution would typically begin with a maximally entangled universal state.

As I noted in reference 1, one can observe the decoherence process experimentally, but that observation does not demonstrate that einselection occurs in a unitary-only dynamics or that classicality emerges in such a dynamics. A key missing ingredient in quantum Darwinism is some real physical randomization process, such as collapse, that could create an observer-independent, physical partitioning at the quantum level. Without such a process, quantum Darwinism contains the same kind of logical circularity as Boltzmann's *H*-theorem, which attempted to derive irreversible thermodynamic laws from reversible laws. Boltzmann inadvertently smuggled in irreversibility by assuming molecular chaos; quantum Darwinists smuggle in classicality via their partitioning of the universe into distinguishable systems of interest that interact with mutually randomized environmental subsystems.

In his article, Zurek does not address this refutation of quantum Darwinism and repeats the refuted claims and circular assumptions. Similar criticisms of quantum Darwinism's presumption of classically distinguishable primordial systems, raised by Jasmina Jeknić-Dugić, Miroljub Dugić, and collaborators,[2–4] and Chris Fields's concern about the division of primordial degrees of freedom into a classically distinguishable system and environment[5] have also not been countered by proponents of quantum Darwinism.

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References

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Ruth E. Kastner
(rkastner@umd.edu)
University of Maryland
College Park

■ **Zurek replies:** Repeatability is a textbook postulate—not mine, as the comment by Alexia Auffèves and Philippe Grangier suggests. However, I like the idea of a "context," provided its origin is quantum. Using an *ab initio* classical apparatus (made out of quantum atoms!) to supply a context is inconsistent. The Copenhagen interpretation used it as an ingenious and successful *ad hoc* fix, but it cannot be a fundamental solution. The inability to delineate a quantum–classical boundary makes matters worse. Textbooks adopt such a "shut up and calculate" ploy to paper over the inconsistency of their axioms.

Quantum Darwinism and decoherence favor quasi-classical pointer states, accessible indirectly to many observers via the imprints they deposit in the environment. Pointer states in turn depend on the quantum context provided by the environment. They emerge from a quantum substrate and supply context for the quantum states of microsystems.

Quantum theory is universally valid. Quantum Darwinism and decoherence explain why macrosystems behave classically: Decoherence limits the validity of the quantum principle of superposition. Preferred states are a compromise between amplification, which calls for many copies of the original, and the no-cloning theorem. An unknown state can't be cloned, but decoherence can amplify pointer states and disseminate information about them throughout the environment.

Observers access only environment fragments, hence they extract only classical information. Quantum coherence, as explained in my article, is out of reach. Observers will agree about states communicated by environment fragments, but only data about pointer states can be shared.[1] Objective existence arises from epiontic—that is, epistemic and ontological—quantum states via the proliferation of information. Robust, quasi-classical branches and elusive information about them both emerge via amplification-like decoherence.

Deducing the measurement postulates—Born's rule and hermiticity of observables—from a simple, self-consistent credo is an advance. The assumptions, that states inhabit Hilbert space and evolve unitarily, should be judged by what follows from them and not by an intuitive appeal to classical prejudices. After all, counterintuitive assumptions—for example, that the speed of light is independent of an observer's motion—have led to deep and valid consequences.

The comment by Ruth Kastner states that phase randomness is key for decoherence and quantum Darwinism and that it is unlikely. Both are incorrect: Random phases between states are typical when phases can be defined. Moreover, random phases aren't essential for decoherence; an outflow of information suffices. Indeed, standard models—for example, of quantum Brownian motion—often employ environments in equilibrium, for which phases are undefined and the question of their randomness is ill-posed. An initial correlation with the environment complicates calculations,[2] but it does not eliminate decoherence. As difficulties encountered by quantum computing research show, decoherence is generic and hard to avoid.

Quantum Darwinism requires more than decoherence; it relies on an environment that can store and communicate information. Solar radiation enables that,[3] since the Sun is a localized photon source. Quantum Darwinism is impossible in a completely equilibrated environment, whose subsystems cannot store information.

The question of how to define systems is indeed of interest, and I have noted it before.[4] The answer must go beyond decoherence: What constitutes a system depends on interactions that make or break it; molecules, for example, would fall apart if atomic interactions weakened.

There is no reason to complicate matters by making the definition of a system part of the measurement problem. Systems are there from the start—Schrödinger's cat is obviously distinct from the nucleus that determines the cat's fate—and their presence alone does not solve the problem. Indeed, the measurement problem disappears absent a system distinct from a measuring apparatus. Quantum evolution of a universe without parts is deterministic. There is no apparatus to record a definite outcome and so no need to talk about measurement outcomes: There is literally nothing to explain. Recognizing