Quantum Darwinism

Natural selection could explain one of the biggest conundrums of quantum mechanics: The emergence of objective reality.

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FQXi Awardee: Wojciech Zurek

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In 1859, Charles Darwin published *On the Origin of Species* in which he laid forth his theory of natural selection, revolutionizing our understanding of biology in the process. At first glance, Wojciech Zurek shares little in common with Darwin. Born almost a century and a half later, he is a physicist who is far more interested in the spread of quantum information than the dispersal of biological traits. But Zurek is now channeling the biologist to explain one of the deepest mysteries of physics: just how the quantum realm transitions into the classical world we see around us. It's all down to the survival of the fittest.

Zurek, at the Los Alamos National Laboratory in New Mexico, is tackling fundamental issues that standard interpretations of quantum mechanics have struggled with: Does the objective world disappear when nobody is looking? How does it even become "objective" in the first place? Why don't we experience quantum fuzziness in everyday life? And what triggers the transition between the quantum and classical? They are questions that he claims his new theory of *quantum Darwinism* can answer.

Growing up in Bielsko-Biala in Poland in the 1960s, Zurek was no ordinary teenager. Even before he finished high school, he cajoled his father into buying him a set of *The Feynman Lectures in Physics*, which had just been translated into Polish. "The first few volumes had the air of amazement and surprise and astonishment at how the universe works, and at how much we can understand about how it works," says Zurek. It was the beginning of an obsession.

That obsession received a major boost when Zurek moved to Austin, Texas, to do his Ph.D. There he worked with the venerable John Wheeler—a fundamental contributor to the fields of quantum mechanics and general relativity, among others. "The time when I realized I could really contribute, rather than just stand by and be amazed, was when I was with Johnny," says Zurek.

That transformation had as much to do with Wheeler's approach to problem-solving, as it did with his formidable achievements in quantum theory. Making mistakes in search for truth was understood to be an integral part of research. "Not being afraid of saying 'I don't know,' and, in fact, using that admission of ignorance as a springboard to make progress was something I hadn't realized, at least not with that clarity," says Zurek. "You really need to be amazed and surprised and puzzled before you get somewhere really interesting."

Emerging Reality

Above all, Zurek and Wheeler were puzzled by one of the central questions that haunts quantum mechanics: How does an objective reality emerge from the quantum world? One of the key distinctions between a quantum object and a classical object is that the former can exist in a superposition of different states. For instance, an electron can be in two places at once. But that superposition only lasts as long as we don't look at the object, or measure it. Once we do, it snaps into one state.

How does such a quantum object become classical, choosing just one definitive state? The question has troubled physicists since the dawn of quantum mechanics, with *wavefunction collapse* and *parallel universes* being invoked as alternative explanations (see "Copenhagen vs. Many Worlds: And the Winner Is…"). But neither has been able to explain the actual mechanism through which classical reality emerges, or how and why the transformation is triggered by observations.

It may seem like an esoteric problem,

QUANTUM INTERACTIONS, COLOSSAL LEGACY
The late John Wheeler (center) inspired (left to right) Bill Wooters, Kip Thorne, Wojciech Zurek & Bill Unruh

but the growing interest in quantum computing has lent it immediacy. Superposition lies at the heart of the promise of quantum computing. The idea is that because quantum systems, such as electrons, can exist in a superposition of states, they can encode a superposition of possibilities, and, therefore, carry out a superposition of computations simultaneously. In a classical computer, the absence or presence of an electron can encode either a '0'or a '1'; in a quantum computer, superposition could represent both simultaneously. This means that, in theory, quantum computers can perform exponentially greater numbers of calculations using the same number of electrons as a classical computer.

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>
> - *Frank Wilhelm*

For this to happen in practice, a quantum computer must maintain its superposition of states long enough to perform significant calculations. But that's easier said than done; it's clear that the world we perceive doesn't exist in a superposition of quantum states. While those building quantum computers fret about not destroying the superposition, theorists wonder why it gets destroyed in the first place.

This is where Zurek comes in. He has focused his efforts on the notion of *decoherence*, first mooted by Dieter Zeh of the University of Heidelberg in 1970. According to decoherence theory, a quantum system can only remain in a superposition of states (that is, remain *coherent*) as long as it is isolated from its environment. As soon as the environment—which includes everything from air molecules to photons—enters the frame, coherence flies out of the window.

Decoherence argues that the reason we don't see macroscopic objects in a superposition of quantum states is because they cannot be isolated from their environment. It doesn't take a conscious observer carrying out a measurement to snap an object from a quantum to a classical state, just a nudge from its surroundings.

Survival of the Fittest

But that still doesn't explain which quantum states become, in effect, classical. It's here that Zurek has made his most important contribution, in papers published from 1981 onwards. His argument centers on the role of the environment, which doesn't just passively disturb the quantum object; instead, it actively determines which classical reality will be selected: "The environment is monitoring the system. It is not just perturbing the system, it is sucking out information.''

They key point is that not all quantum superposition states are created equal—some are more apt to survive in one particular environment than others. The act of information transfer from the quantum system to the environment serves two purposes. First, it destroys fragile quantum states that aren't so well suited to their surroundings. This is *einselection*—**e**nvironment **in**duced super-**selection**—the process that selects these preferred states and spreads the information about

Copenhagen vs. Many Worlds: And the Winner Is...

The conundrum over the quantum to classical transition appeared on the horizon soon after the discovery of quantum mechanics. In the 1920s, quantum behemoths Niels Bohr and Werner Heisenberg, and others, met in Copenhagen and arrived upon the standard interpretation of quantum mechanics: Prior to observation, a quantum object exists as a *wavefunction* that accommodates the superposition of multiple states. The act of observing the system "collapses" the wavefunction and we end up with a classical state.

The problem with the *Copenhagen Interpretation* is that it doesn't describe how this collapse occurs. It also raises the uncomfortable philosophical question of whether an objective reality exists in the absence of observers.

Then in the 1950s, Hugh Everett III—a student of John Wheeler's—came up with an even more radical solution that did away with collapse entirely. He suggested that the entire universe is a quantum object, with every possible outcome of a measurement realized—just in different realities. This leads to a mind-boggling scenario, in which every possible quantum state exists in its own world, a scenario rather simplistically called the "many worlds" interpretation.

So which alternative does Zurek back? He favors decoherence theory, which describes how interaction with the environment gradually destroys a quantum state. But Zurek is quick to point out that decoherence is compatible with both interpretations.

"Collapse has metaphysical connotations. It begins to touch on whether you think like Bohr or Everett," says Zurek. "What I am trying to do, among other things, is to try and stay away from taking a side."

them throughout the environment.

But this does not yet explain the emergence of an objective reality. After all, these einselected quantum states could still be perturbed by a direct measurement carried out by an observer.

Quantum Photography

Zurek's current research centers on the idea that the environment also becomes a "witness" to the state of the system. What this means is that multiple copies of the states that survive interaction with their surroundings are disseminated throughout the environment—as though the environment is taking photographs of the preferred states and passing them on. This survival-of-the-fittest-states and their proliferation throughout the environment has been dubbed *quantum Darwinism*.

Quantum Darwinism ensures that different observers will see the same objective reality because they are most likely to intercept a copy of the same stable state. "The main idea of quantum Darwinism is that we almost never do any direct measurement on anything," says Zurek. Instead, the environment acts as a witness, or as a communication channel. "It is like a big advertising billboard, which floats multiple copies of the information about our universe all over the place."

"Zurek has a great talent for raising important points and putting things—which other people may have been observing on the side in their calculations—front and center," says Frank Wilhelm of the Institute for Quantum Computing in Waterloo, Canada. Wilhelm admires Zurek's work for provoking a debate on the foundations of quantum mechanics.

Bill Unruh, a quantum theorist at the University of British Columbia in Vancouver also commends Zurek for wrestling with issues that most ignore. "It is a problem that most people leave on the side of their table, to think about while they are sitting in the bath and not to take too seriously," says Unruh. "He's been one of the very few people in the world who has been willing to take it seriously."

However, Unruh adds that it is too early to say whether Zurek's ideas can provide the final answer to the quantum conundrum.

If Zurek wants to win everyone over to his way of thinking, he must address one big question: Can we verify quantum Darwinism experimentally? Zurek has been awarded a $75,000 grant from the Foundational Questions Institute to develop models that make concrete predictions that experimenters can test. He's got good reason to be optimistic as computer simulations are already showing signs of quantum Darwinism at play (see "Natural Selection in Action").

Zurek's next step is to make additional testable predictions. For example, what fraction of the environment is needed to extract a certain amount of information about the quantum system? This requires extending his work to include impure environments. So far, theoretical models have involved idealized pure environments, or "clean slates," on which only the information about the system will be "written." But in realistic cases, the slate is not clean—the environment could already be partially occupied with information about other entities.

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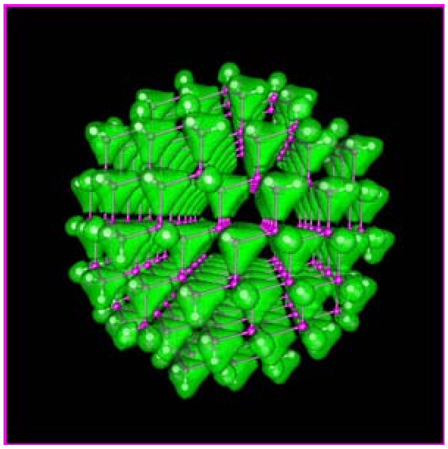
> - *Wojciech Zurek*

Of course, there is always a danger that a lifetime of work can be undermined by experiments; Zurek has been working on theories of quantum information for close to 30 years. Many of his theories have been confirmed by experiment, but quantum Darwinism is still new and awaiting tests. Zurek, however, is unperturbed. After all, standing up to experimental testing is essential for any physics theory that wants to be taken seriously. In a world full of alternative ideas, only the fittest will survive.



WILL QUANTUM DOTS prove quantum Darwinism?
(*Image: Lin-Wang Wang, Lawrence Berkeley National Laboratory*)

Natural Selection in Action

Darwin could back up his ideas on natural selection by looking at the characteristics of birds and animals. But how can we catch "quantum natural selection" in the act?

In 2007, Wojciech Zurek of the Los Alamos National Laboratory in New Mexico, and his former student, Robin Blume-Kohout of the California Institute of Technology in Pasadena, developed a computer model in which a "quantum pendulum" was set oscillating according to the laws of quantum mechanics. Such an oscillator can exist in a superposition of states, simultaneously present in all possible locations along its path. The duo modeled the environment by including thousands of other pendulums nearby, each "swinging" at a different frequency.

If quantum Darwinism is correct, the environmental pendulums should record a copy of the quantum pendulum's position. And that is what it did. Multiple copies of the same quantum state were replicated throughout the environment. The model showed quantum Darwinism in action.

In addition, early this year, Roland Brunner of the University of Leoben in Austria and his colleagues showed quantum Darwinism, in theory, in an array of quantum dots—nanoscale bits of semiconducting materials, with electrons that can exist in a superposition of states.

The team studied what happens when multiple dots are arrayed in series and also interact with the environment. They found that two adjacent quantum dots gave rise to a special quantum state that was peculiar to their interaction, and not merely a combination of states of individual quantum dots.

More importantly, they showed that they could find out about these special states by looking at individual quantum dots. It's as if stable states had been copied and imprinted on all the individual dots. All observers would see the same objective reality—thanks to quantum Darwinism.