

## COMMENTARY

# Many lives in many worlds

Accepting quantum physics to be universally true, argues Max Tegmark, means that you should also believe in parallel universes.

Almost all of my colleagues have an opinion about it, but almost none of them have read it. The first draft of Hugh Everett's PhD thesis, the shortened official version of which celebrates its 50th birthday this year, is buried in the out-of-print book *The Many-Worlds Interpretation of Quantum Mechanics*. I remember my excitement on finding it in a small Berkeley book store back in grad school, and still view it as one of the most brilliant texts I've ever read.

By the time Everett started his graduate work with John Archibald Wheeler at Princeton University in New Jersey quantum mechanics had chalked up stunning successes in explaining the atomic realm, yet debate raged on as to what its mathematical formalism really meant. I was fortunate to get to discuss quantum mechanics with Wheeler during my postdoctorate years in Princeton, but never had the chance to meet Everett.

Quantum mechanics specifies the state of the Universe not in classical terms, such as the positions and velocities of all particles, but in terms of a mathematical object called a wavefunction. According to the Schrödinger equation, this wavefunction evolves over time in a deterministic fashion that mathematicians term 'unitary'. Although quantum mechanics is often described as inherently random and uncertain, there is nothing random or uncertain about the way the wavefunction evolves.

The sticky part is how to connect this wavefunction with what we observe. Many legitimate wavefunctions correspond to counterintuitive situations, such as Schrödinger's cat being dead and alive at the same time in a 'superposition' of states. In the 1920s, physicists explained away this weirdness by postulating that the wavefunction 'collapsed' into some random but definite classical outcome whenever someone made an observation. This add-on had the virtue of explaining observations, but rendered the theory incomplete, because there was no mathematics specifying what constituted an observation — that is, when the wavefunction was supposed to collapse.

Everett's theory is simple to state but has complex consequences, including parallel universes. The theory can be summed up by saying that the Schrödinger equation applies



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Is it only in fiction that we can experience parallel lives? If atoms can be in two places at once, so can you.

at all times; in other words, that the wavefunction of the Universe never collapses. That's it — no mention of parallel universes or splitting worlds, which are implications of the theory rather than postulates. His brilliant insight was that this collapse-free quantum theory is, in fact, consistent with observation. Although it predicts that a wavefunction describing one classical reality gradually evolves into a wavefunction describing a superposition of many such realities — the many worlds — observers subjectively experience this splitting merely as a slight randomness (see 'Not so random', overleaf), with probabilities consistent with those calculated using the wavefunction-collapse recipe.

## Gaining acceptance

It is often said that important scientific discoveries go through three phases: first they are completely ignored, then they are violently attacked, and finally they are brushed aside as well known. Everett's discovery was no exception: it took more than a decade before it started getting noticed. But it was too late for Everett, who left academia disillusioned<sup>1</sup>.

Everett's no-collapse idea is not yet at stage three, but after being widely dismissed as too crazy during the 1970s and 1980s, it has gradually gained more acceptance. At an informal poll taken at a conference on the foundations of quantum theory in 1999, physicists rated the idea more highly than the alternatives, although many more physicists were still 'undecided'<sup>2</sup>. I believe the upward trend is clear.

Why the change? I think there are several reasons. Predictions of other types of parallel universes from cosmological inflation and string theory have increased tolerance for weird-sounding ideas. New experiments have demonstrated quantum weirdness in ever larger systems. Finally, the discovery of a process known as decoherence has answered crucial questions that Everett's work had left dangling.

For example, if these parallel universes exist, why don't we perceive them? Quantum superpositions cannot be confined — as most quantum experiments are — to the microworld. Because you are made of atoms, then if atoms can be in two places at once in superposition, so can you.

The breakthrough came in 1970 with a seminal paper by H. Dieter Zeh, who showed

**"If we dismiss theories because they seem weird, we risk missing true breakthroughs."**

that the Schrödinger equation itself gives rise to a type of censorship. This effect became known as ‘decoherence’, and was worked out in great detail by Wojciech Zurek, Zeh and others over the following decades. Quantum superpositions were found to remain observable only as long as they were kept secret from the rest of the world. The quantum card in our example (see ‘Not so random’) is constantly bumping into air molecules, photons and so on, which thereby find out whether it has fallen to the left or to the right, destroying the coherence of the superposition and making it unobservable. Decoherence also explains why states resembling classical physics have special status: they are the most robust to decoherence.

### Science or philosophy?

The main motivation for introducing the notion of random wavefunction collapse into quantum physics had been to explain why we perceive probabilities and not strange macroscopic superpositions. After Everett had shown that things would appear random anyway (see ‘Not so random’) and decoherence had been found to explain why we never perceive anything strange, much of this motivation was gone. Even though the wavefunction technically never collapses in the Everett view, it is generally agreed that decoherence produces an effect that looks like a collapse and smells like a collapse.

In my opinion, it is time to update the many quantum textbooks that introduce wavefunction collapse as a fundamental postulate of quantum mechanics. The idea of collapse still has utility as a calculational recipe, but students should be told that it is probably not a fundamental process violating the Schrödinger equation so as to avoid any subsequent confusion. If you are considering a quantum textbook that does not mention Everett and decoherence in the index, I recommend buying a more modern one.

After 50 years we can celebrate the fact that Everett’s interpretation is still consistent with quantum observations, but we face another pressing question: is it science or mere philosophy? The key point is that parallel universes are not a theory in themselves, but a prediction of certain theories. For a theory to be falsifiable, we need not observe and test all its predictions — one will do.

Because Einstein’s general theory of relativity has successfully predicted many things we can observe, we also take seriously its predictions for things we cannot, such as the internal structure of black holes. Analogously, successful predictions by unitary quantum mechanics have made scientists take more seriously its other predictions, including parallel universes.

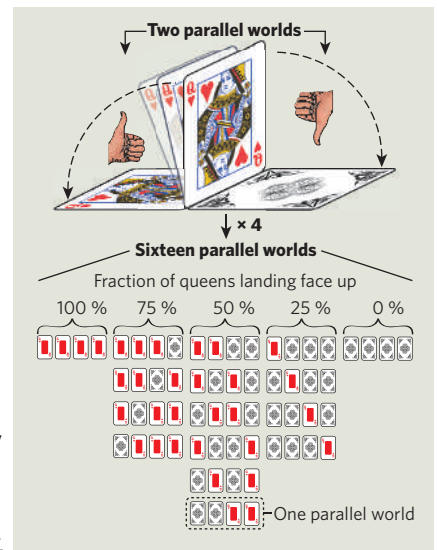
Moreover, Everett’s theory is falsifiable by future lab experiments: no matter how large a system they probe, it says, they will not observe the wavefunction collapsing. Indeed, collapse-free superpositions have been demonstrated in systems with many atoms,

### Not so random

According to quantum theory, a card perfectly balanced on its edge will fall down in what is known as a ‘superposition’ — the card really is in two places at once. If a gambler bets money on the queen landing face up, the gambler’s own state changes to become a superposition of two possible outcomes — winning or losing the bet. In either of these parallel worlds, the gambler is unaware of the other outcome and feels as if the card fell randomly.

If the gambler repeats this game four times in a row, there will be 16 ( $2 \times 2 \times 2 \times 2$ ) possible outcomes, or parallel worlds. In most of these worlds, it will seem that queens occur randomly, with about 50% probability. Only in two worlds will all four cards land the same way up. If the game is continued many more times, almost every gambler in each of the worlds will conclude that the laws of probability apply even though the underlying physics is not random and, as Einstein put it, “God does not play dice”.

M.T.



such as carbon-60 molecules. Several groups are now attempting to create quantum superpositions of objects involving  $10^{17}$  atoms or more, tantalizingly close to our human macroscopic scale. There is also a global effort to build quantum computers which, if successful, will be able to factor numbers exponentially faster than classical computers, effectively performing parallel computations in Everett’s parallel worlds.

### The bird perspective

So Everett’s theory is testable and so far agrees with observation. But should you really believe it? When thinking about the ultimate nature of reality, I find it useful to distinguish between two ways of viewing a physical theory: the outside view of a physicist studying its mathematical equations, like a bird surveying a landscape from high above, and the inside view of an observer living in the world described by the equations, like a frog being watched by the bird.

From the bird perspective, Everett’s multiverse is simple. There is only one wavefunction, and it evolves smoothly and deterministically over time without any kind of splitting or parallelism. The abstract quantum world described by this evolving wavefunction contains within it a vast number of classical parallel storylines (worlds), continuously splitting and merging, as well as a number of quantum phenomena that lack a classical description. From their frog perspective, observers perceive only a tiny fraction of this full reality, and they perceive the splitting of classical storylines as quantum randomness.

What is more fundamental — the frog perspective or the bird perspective? In other words, what is more basic to you: human language or mathematical language? If you opt for the former, you would probably prefer a ‘many worlds’ interpretation of quantum mechanics, where mathematical simplicity is sacrificed to

collapse the wavefunction and eliminate parallel universes.

But if you prefer a simple and purely mathematical theory, then you — like me — are stuck with the many-worlds interpretation. If you struggle with this you are in good company: in general, it has proved extremely difficult to formulate a mathematical theory that predicts everything we can observe and nothing else — and not just for quantum physics.

Moreover, we should expect quantum mechanics to feel counterintuitive, because evolution endowed us with intuition only for those aspects of physics that had survival value for our distant ancestors, such as the trajectories of flying rocks.

The choice is yours. But I worry that if we dismiss theories such as Everett’s because we can’t observe everything or because they seem weird, we risk missing true breakthroughs, perpetuating our instinctive reluctance to expand our horizons. To modern ears the Shapley–Curtis debate of 1920 about whether there was really a multitude of galaxies (parallel universes by the standards of the time) sounds positively quaint.

Everett asked us to acknowledge that our physical world is grander than we had imagined, a humble suggestion that is probably easier to accept after the recent breakthroughs in cosmology than it was 50 years ago. I think Everett’s only mistake was to be born ahead of his time. In another 50 years, I believe we will be more used to the weird ways of our cosmos, and even find its strangeness to be part of its charm.

In this Universe, Max Tegmark is a physicist at the Massachusetts Institute of Technology, Cambridge, Massachusetts, USA.

1. Shikhovtsev, E. *Biographical Sketch of Hugh Everett, III* <http://space.mit.edu/home/tegmark/everett/> (2003).
2. Tegmark, M. & Wheeler, J. A. <http://arxiv.org/pdf/quant-ph/0101077> (2001).

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