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The Quantum Multiverse

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Author
Nomura, Yasunori

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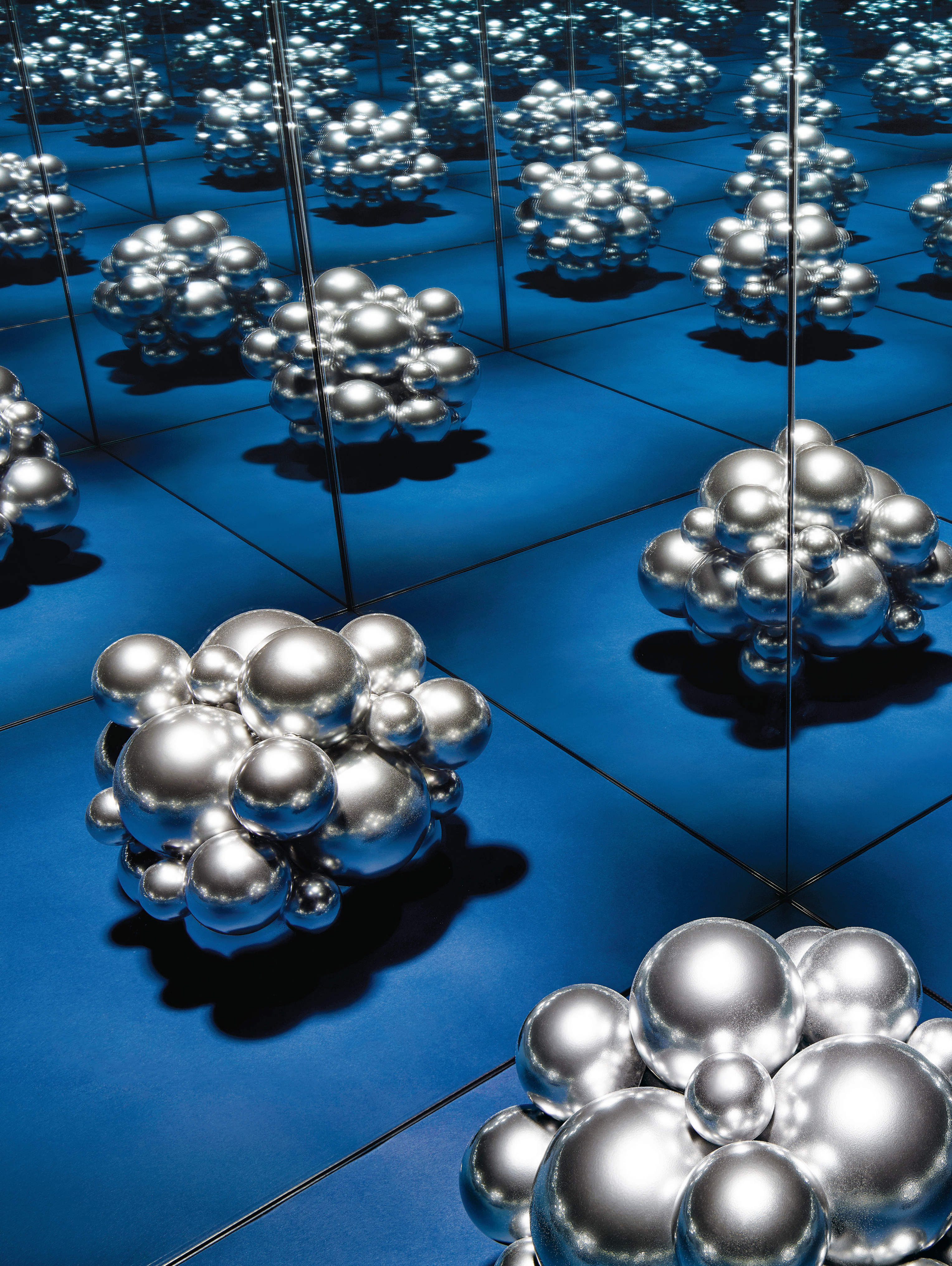
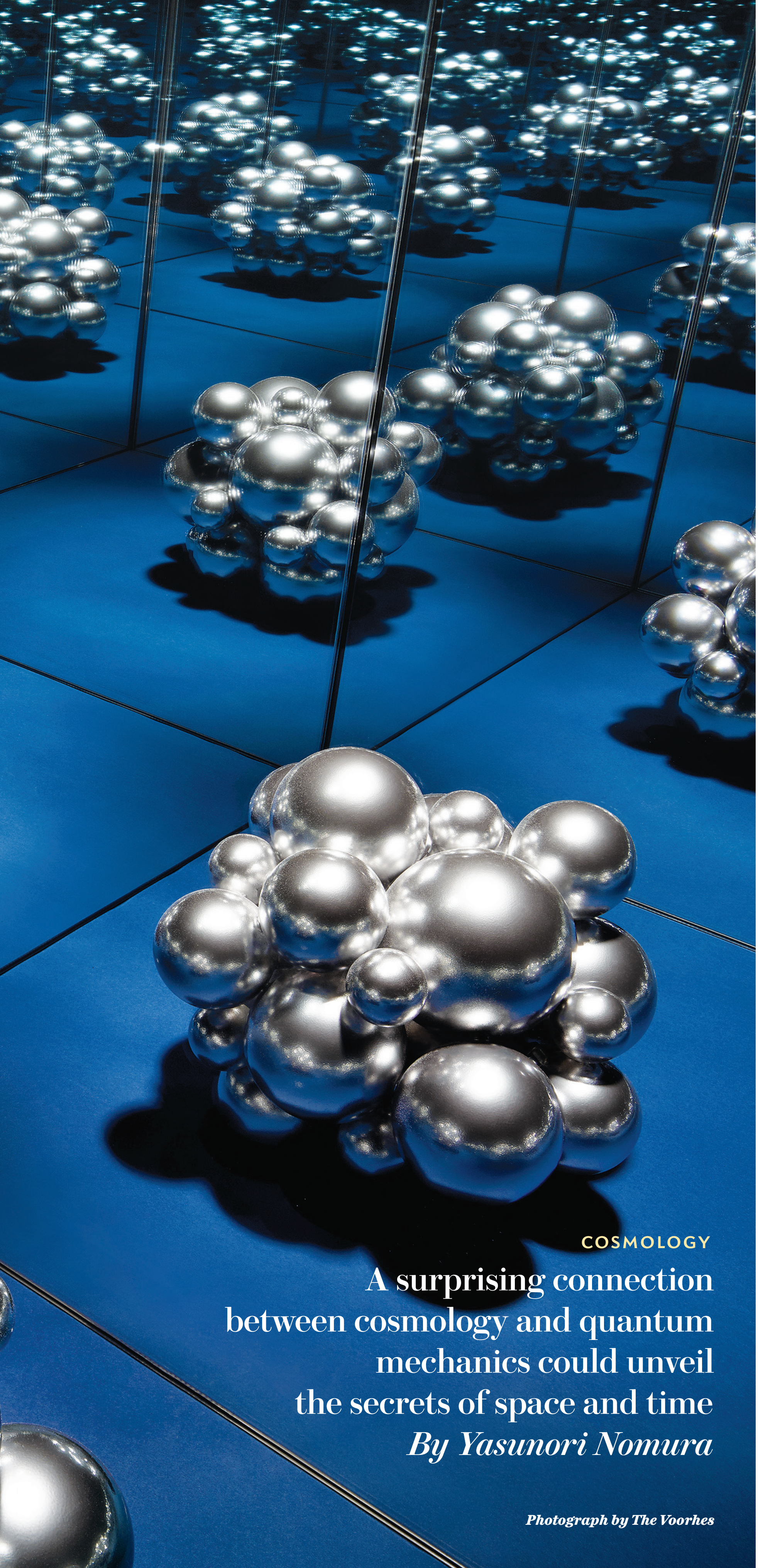


THE QUANTUM MULTIVERSE



COSMOLOGY

A surprising connection between cosmology and quantum mechanics could unveil the secrets of space and time

By Yasunori Nomura

Photograph by The Voorhes

Yasunori Nomura is a professor of physics and director of the Berkeley Center for Theoretical Physics at the University of California, Berkeley. He is also a senior faculty scientist at Lawrence Berkeley National Laboratory and a principal investigator at the University of Tokyo's Kavli Institute for the Physics and Mathematics of the Universe.

MANY COSMOLOGISTS NOW ACCEPT THE EXTRAORDINARY IDEA THAT what seems to be the entire universe may actually be only a tiny part of a much larger structure called the multiverse. In this picture, multiple universes exist, and the rules we once assumed were basic laws of nature take different forms in each; for example, the types and properties of elementary particles may differ from one universe to another.

The multiverse idea emerges from a theory that suggests the very early cosmos expanded exponentially. During this period of "inflation," some regions would have halted their rapid expansion sooner than others, forming what are called bubble universes, much like bubbles in boiling water. Our universe would be just one of these bubbles, and beyond it would lie infinitely more.

The idea that our entire universe is only a part of a much larger structure is, by itself, not as outlandish as it sounds. Throughout history scientists have learned many times over that the visible world is far from all there is. Yet the multiverse notion, with its unlimited number of bubble universes, does present a major theoretical problem: it seems to erase the ability of the theory to make predictions—a central requirement of any useful theory. In the words of Alan Guth of the Massachusetts Institute of Technology, one of the creators of inflation theory, "in an eternally inflating universe, anything that can happen will happen; in fact, it will happen an infinite number of times."

In a single universe where events occur a finite number of times, scientists can calculate the relative probability of one event occurring versus another by comparing the number of times these events happen. Yet in a multiverse where everything happens an infinite number of times, such counting is not possible, and nothing is more likely to occur than anything else. One can make any prediction one wants, and it is bound to come true in some universe, but that fact tells you nothing about what will go on in our specific world.

This apparent loss of predictive power has long troubled physicists. Some researchers, including me, have now realized that quantum theory—which, in contrast to the multiverse notion, is concerned with the very smallest particles in existence—may, ironically, point the way to a solution. Specifically, the cosmological picture of the eternally inflating multiverse may be mathematically equivalent to the "many worlds" interpretation of quantum mechanics, which attempts to explain how particles can seem to be in many places at once. As we will see, such a connection between the theories not only solves the prediction problem, it may also reveal surprising truths about space and time.

QUANTUM MANY WORLDS

I CAME TO THE IDEA of a correspondence between the two theories after I revisited the tenets of the many-worlds interpretation of quantum mechanics. This concept arose to make sense of some of the stranger aspects of quantum physics. In the quantum world—a nonintuitive place—cause and effect work differently than they do in the macro world, and the outcome of any process is always probabilistic. Whereas in our macroscopic experience, we can predict where a ball will land when it is thrown based on its starting point, speed and other factors, if that ball were a quantum particle, we could only ever say it has a certain chance of ending up here and another chance of ending up there. This probabilistic nature cannot be avoided by knowing more about the ball, the air currents or such details; it is an intrinsic property of the quantum realm. The same exact ball thrown under the same exact conditions will sometimes land at

IN BRIEF

The theory of cosmic inflation, which implies that the early cosmos expanded exponentially, suggests that we live not in a universe but a vast multiverse.

The problem with the multiverse idea, however, is that all events that can occur will occur infinitely many times, ruining the theory's predictive ability.

Physicists realized they can resolve the issue by viewing the multiverse as equivalent to a notion from quantum mechanics called the many-worlds interpretation, which suggests that our universe is one of many that coexist in "probability space" rather than in a single real space.

HUBBLE SPACE TELESCOPE'S Ultra Deep Field shows galaxies as far as 13 billion light-years away. Objects much farther out will forever be beyond reach because the expansion of space causes them to recede faster than the speed of light. This so-called cosmological horizon has important implications for the theory of the multiverse.

COURTESY OF NASA, ESA, S. BECKWITH *STScI* AND HUBBLE DEEP FIELD TEAM

point A and other times at point B. This conclusion may seem strange, but the laws of quantum mechanics have been confirmed by innumerable experiments and truly describe how nature works at the scale of subatomic particles and forces.

In the quantum world, we say that after the ball is thrown, but before we look for its landing spot, it is in a so-called superposition state of outcomes A and B—that is, it is neither at point A nor point B but located in a probabilistic haze of *both* points A and B (and many other locations as well). Once we look, however, and find the ball in a certain place—say, point A—then anyone else who examines the ball will also confirm that it sits at A. In other words, before any quantum system is measured, its outcome is uncertain, but afterward all subsequent measurements will find the same result as the first.

In the conventional understanding of quantum mechanics, called the Copenhagen interpretation, scientists explain this shift by saying that the first measurement changed the state of the system from a superposition state to the state A. But although the Copenhagen interpretation does predict the outcomes of laboratory experiments, it leads to serious difficulties at the conceptual level. What does the "measurement" really mean, and why does it change the state of the system from a superposition of possibilities to a single certainty? Does the change of state occur when a dog or even a fly observes the system? What about when a molecule in the air interacts with the system, which we expect to be occurring all the time yet which we do not usually treat as a measurement that can interfere with the outcome? Or is there some special physical significance in a human consciously learning the state of the system?

In 1957 Hugh Everett, then a graduate student at Princeton University, developed the many-worlds interpretation of quantum mechanics that beautifully addresses this issue—although at the time many received it with ridicule, and the idea is still less favored than the Copenhagen interpretation. Everett's key insight was that the state of a quantum system reflects the state of the *whole* universe around it, so that we must include the observer in a complete description of the measurement. In other words, we cannot consider the ball, the wind and the hand that throws it in isolation—we must also include in the fundamental description the person who comes along to inspect its landing spot, as well as everything else in the cosmos at that time. In this picture, the quantum state after the measurement is still a superposition—not just a superposition of two landing spots but of two entire worlds! In the first world, the observer finds that the state of the system has changed to A, and therefore any observer in this particular world will obtain result A in all subsequent measurements. But when the measurement was made, another universe split off from the first in which the observer finds, and keeps finding, that the ball landed at point B. This feature explains why the observer—let us say it is a man—thinks that his measurement changes the state of the system; what actually happens is that when he makes a measurement (interacts with the system), he himself divides into two different people who live in two different parallel worlds corresponding to two separate outcomes, A and B.

According to this picture, humans making measurements have no special significance. The state of the entire world continuously branches into many possible parallel worlds that co-

Inflation Meets Many Worlds

The theory of inflation suggests that our universe is one of infinitely many that formed when the very early cosmos expanded exponentially. This picture of a multiverse, however, seems to destroy the theory's ability to make predictions because anything that can happen in an infinite multiverse will happen infinitely many times. The problem is solved, however, if the inflationary multiverse is equivalent to the "many worlds" interpretation of quantum mechanics, which posits that all these infinite universes coexist not in a single real space but in "probability space."

INFLATIONARY MULTIVERSE

This theory holds that during inflation certain regions would have slowed their rapid expansion before others, forming bubbles that became universes unto themselves. As time went on, more and more patches slowed to form new bubbles within the larger inflating space, which went on expanding eternally. Our universe is just one of these bubbles.

MANY WORLDS

Quantum mechanics says that a particle, rather than being hidden under either cup A or cup B, actually exists under both cups with a certain probability (*denoted by yellow wave*) of being found in any given place. Only when an observer turns over the cups to check does the particle "choose" to be in one of the two possible locations. The many-worlds interpretation suggests that every time an observer performs such a measurement, two new universes branch off—one where the particle ended up being under cup A and one where the particle resided under cup B.

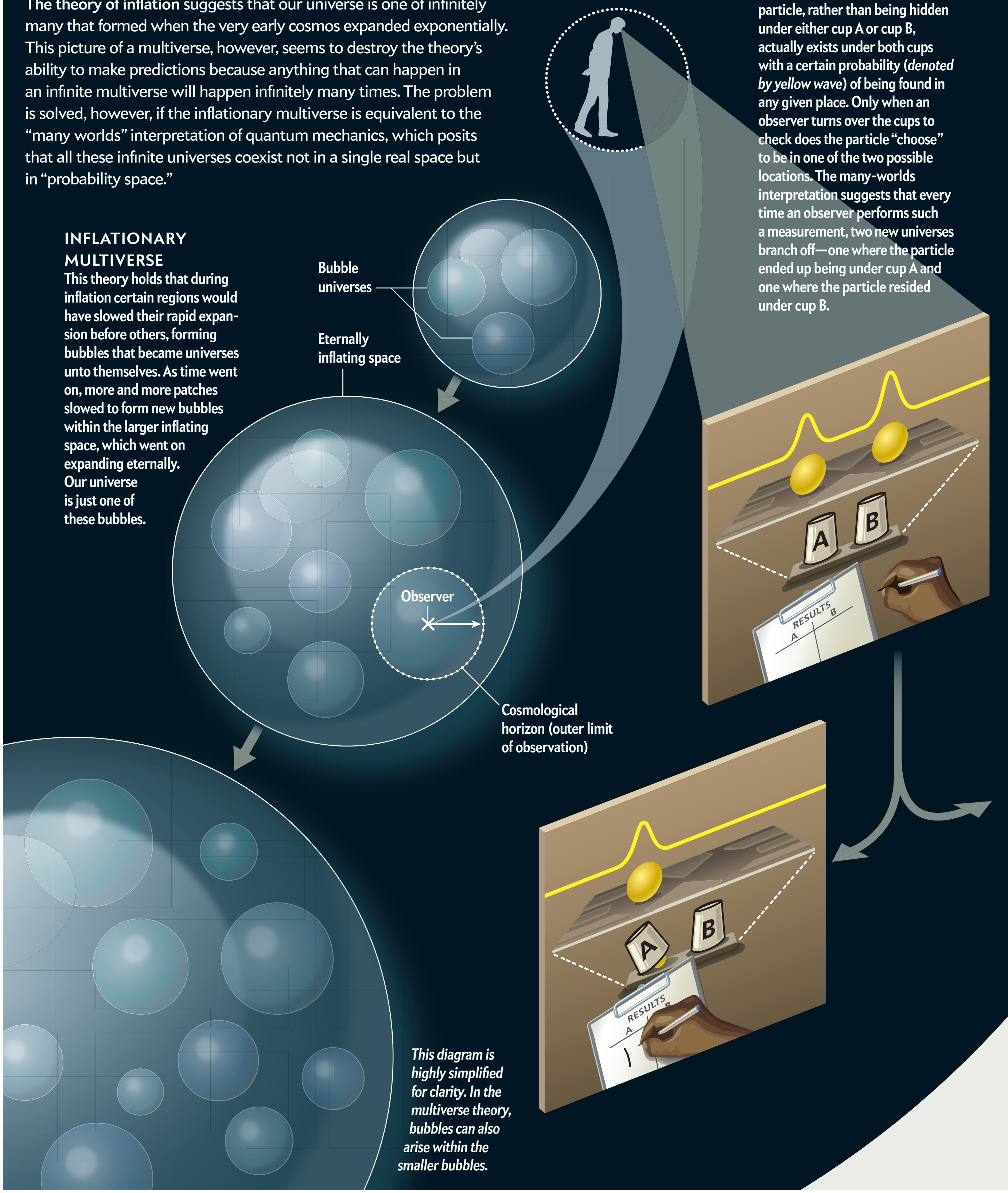
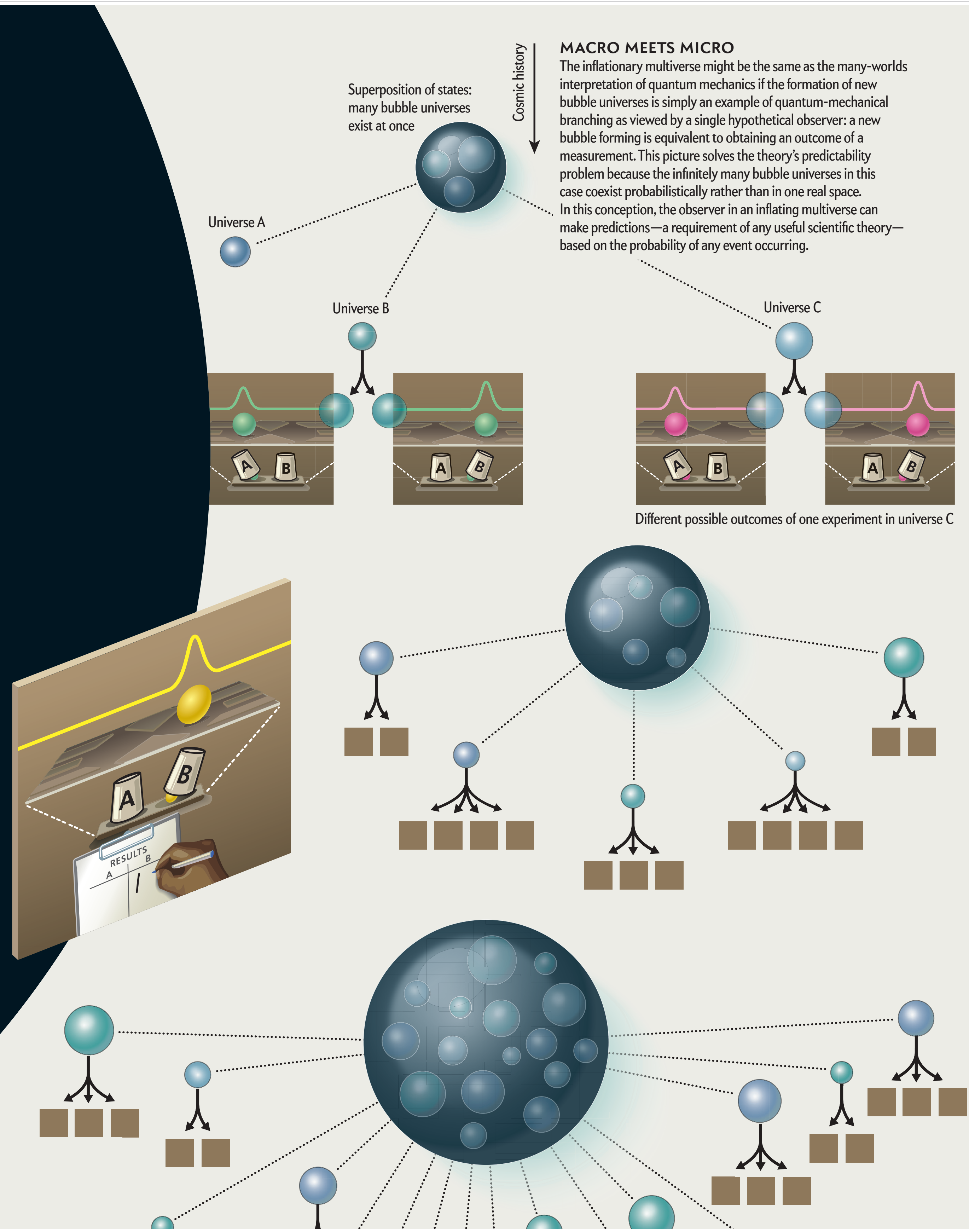


Illustration by Jen Christiansen



MACRO MEETS MICRO

The inflationary multiverse might be the same as the many-worlds interpretation of quantum mechanics if the formation of new bubble universes is simply an example of quantum-mechanical branching as viewed by a single hypothetical observer: a new bubble forming is equivalent to obtaining an outcome of a measurement. This picture solves the theory's predictability problem because the infinitely many bubble universes in this case coexist probabilistically rather than in one real space. In this conception, the observer in an inflating multiverse can make predictions—a requirement of any useful scientific theory—based on the probability of any event occurring.

exist as a superposition. A human observer, being a part of nature, cannot escape from this cycle—the observer keeps splitting into many observers living in many possible parallel worlds, and all are equally "real." An obvious but important implication of this picture is that everything in nature obeys the laws of quantum mechanics, whether small or large.

What does this interpretation of quantum mechanics have to do with the multiverse discussed earlier, which seems to exist in a continuous real space rather than as parallel realities? In 2011 I argued that the eternally inflating multiverse and quantum-mechanical many worlds à la Everett are the same concept in a specific sense. In this understanding, the infinitely large space associated with eternal inflation is a kind of "illusion"—the many bubble universes of inflation do not all exist in a single real space but represent the possible different branches on the probabilistic tree. Around the same time that I made this proposal, Raphael Bousso of the University of California, Berkeley, and Leonard Susskind of Stanford University put forth a similar idea. If true, the many-worlds interpretation of the multiverse would mean that the laws of quantum mechanics do not operate solely in the microscopic realm—they also play a crucial role in determining the global structure of the multiverse even at the largest distance scales.

I and other physicists are also pursuing the quantum multiverse idea further. How can we determine the quantum state of the entire multiverse? What is time, and how does it emerge?

BLACK HOLE QUANDARY

TO BETTER EXPLAIN how the many-worlds interpretation of quantum mechanics could describe the inflationary multiverse, I must digress briefly to talk about black holes. Black holes are extreme warps in spacetime whose powerful gravity prevents objects that fall into them from escaping. As such, they provide an ideal testing ground for physics involving strong quantum and gravitational effects. A particular thought experiment about these entities reveals where the traditional way of thinking about the multiverse goes off track, thereby making prediction impossible.

Suppose we drop a book into a black hole and observe from the outside what happens. Whereas the book itself can never escape the black hole, theory predicts that the information in the book will not be lost. After the book has been shredded by the black hole's gravity and after the black hole itself has gradually evaporated by emitting faint radiation (a phenomenon known as Hawking radiation, discovered by physicist Stephen Hawking of the University of Cambridge), outside observers can reconstruct all the information contained in the initial book by closely examining the radiation released. Even before the black hole has completely evaporated, the book's information starts to slowly leak out via each piece of Hawking radiation.

Yet a puzzling thing occurs if we think about the same situation from the viewpoint of someone who is falling into the black hole along with the book. In this case, the book seems to simply pass through the boundary of the black hole and stay inside. Thus, to this inside observer, the information in the book is also contained within the black hole forever. On the other hand, we have just argued that from a distant observer's point of view, the information will be *outside*. Which is correct? You might think that the information is simply duplicated: one copy inside and the other outside. Such a solution, however, is impossible. In quantum mechanics, the so-called no-cloning theorem prohibits faithful, full copying of information. Therefore, it seems that the two pictures seen by the two observers cannot both be true.

Physicists Gerard 't Hooft of Utrecht University in the Netherlands, Susskind and their collaborators have proposed the following solution: the two pictures can both be valid but not at the same time. If you are a distant observer, then the information is outside. You need not describe the interior of the black hole, because you can never access it even in principle; in fact, to avoid cloning information, you must think of the interior spacetime as nonexistent. On the other hand, if you are an observer falling into the hole, then the interior is all you have, and it contains the book and its information. This view, however, is possible only at the cost of ignoring the Hawking radiation being emitted from the black hole—but such a conceit is allowed because you yourself have crossed the black hole boundary and accordingly are trapped inside, cut off from the radiation emitted from the boundary. There is no inconsistency in either of these two viewpoints; only if you artificially "patch" the two, which you can never physically do, given that you cannot be both a distant and a falling observer at the same time, does the apparent inconsistency of information cloning occur.

COSMOLOGICAL HORIZONS

THIS BLACK HOLE CONUNDRUM may seem unrelated to the issue of how the many-worlds notion of quantum mechanics and the multiverse can be connected, but it turns out that the boundary of a black hole is similar in important ways to the so-called cosmological horizon—the boundary of the spacetime region within which we can receive signals from deep space. The horizon exists because space is expanding exponentially, and objects farther than this cutoff are receding faster than the speed of light, so any message from them can never reach us. The situation, therefore, is akin to a black hole viewed by a distant observer. Also, as in the case of the black hole, quantum mechanics requires an observer inside the horizon to view spacetime on the other side of the boundary—in this case, the exterior of the cosmological horizon—as nonexistent. If we consider such spacetime in addition to the information that can be retrieved from the horizon later (analogous to Hawking radiation in the black hole case), then we are overcounting the information. This prob-

SCIENTIFIC AMERICAN ONLINE Read more about the many-worlds interpretation of quantum mechanics at ScientificAmerican.com/jun2017/multiverse

lem implies that any description of the quantum state of the universe should include only the region within (and on) the horizon—in particular, there can be no infinite space in any single, consistent description of the cosmos.

If a quantum state reflects only the region within the horizon, then where is the multiverse, which we thought existed in an eternally inflating infinite space? The answer is that the creation of bubble universes is probabilistic, like any other process in quantum mechanics. Just as a quantum measurement could spawn many different results distinguished by their probability of occurring, inflation could produce many different universes, each with a different probability of coming into being. In other words, the quantum state representing eternally inflating space is a superposition of worlds—or branches—representing different universes, with each of these branches including only the region within its own horizon.

Because each of these universes is finite, we avoid the problem of predictability that was raised by the prospect of an infinitely large space that encompasses all possible outcomes. The multiple universes in this case do not all exist simultaneously in real space—they coexist only in "probability space," that is, as possible outcomes of observations made by people living inside each world. Thus, each universe—each possible outcome—retains a specific probability of coming into being.

This picture unifies the eternally inflating multiverse of cosmology and Everett's many worlds. Cosmic history then unfolds like this: the multiverse starts from some initial state and evolves into a superposition of many bubble universes. As time passes, the states representing each of these bubbles further branch into more superpositions of states representing the various possible outcomes of "experiments" performed within those universes (these need not be scientific experiments—they can be any physical processes). Eventually the state representing the whole multiverse will thus contain an enormous number of branches, each of which represents a possible world that may arise from the initial state. Quantum-mechanical probabilities therefore determine outcomes in cosmology and in microscopic processes. The multiverse and quantum many worlds are really the same thing; they simply refer to the same phenomenon—superposition—occurring at vastly different scales.

In this new picture, our world is only one of all possible worlds that are allowed by the fundamental principles of quantum physics and that exist simultaneously in probability space.

THE REALM BEYOND

TO KNOW IF THIS IDEA is correct, we would want to test it experimentally. But is that feasible? It turns out that discovery of one particular phenomenon would lend support to the new thinking. The multiverse could lead to a small amount of negative spatial curvature in our universe—in other words, objects would travel through space not along straight lines as in a flat cosmos but along curves, even in the absence of gravity. Such curvature could happen because, even though the bubble universes are finite as seen from the perspective of the entire multiverse, observers inside a bubble would perceive their universe to be infinitely large, which would make space seem negatively curved (an example of negative curvature is the surface of a saddle, whereas the surface of a sphere is positively curved). If we were inside one such bubble, space should likewise appear to us to be bent.

Evidence so far indicates that the cosmos is flat, but experiments studying how distant light bends as it travels through the cosmos are likely to improve measures of the curvature of our universe by about two orders of magnitude in the next few decades. If these experiments find any amount of negative curvature, they will support the multiverse concept because, although such curvature is technically possible in a single universe, it is implausible there. Specifically, a discovery supports the quantum multiverse picture described here because it can naturally lead to curvature large enough to be detected, whereas the traditional inflationary picture of the multiverse tends to produce negative curvature many orders of magnitude smaller than we can hope to measure.

Interestingly, the discovery of positive curvature would falsify the multiverse notion discussed here because inflation theory suggests that bubble universes could produce only negative curvature. On the other hand, if we are lucky, we may even see dramatic signs of a multiverse—such as a remnant from a "collision" of bubble universes in the sky, which may be formed in a single branch in the quantum multiverse. Scientists are, however, far from certain if we will ever detect such signals.

I and other physicists are also pursuing the quantum multiverse idea further on a theoretical level. We can ask fundamental questions such as, How can we determine the quantum state of the entire multiverse? What is time, and how does it emerge? The quantum multiverse picture does not immediately answer these questions, but it does provide a framework to address them. Lately, for instance, I have found that constraints imposed by the mathematical requirement that our theory must include rigorously defined probabilities may enable us to determine the unique quantum state of the entire multiverse. These constraints also suggest that the overall quantum state stays constant even though a physical observer, who is a part of the multiverse state, will see that new bubbles constantly form. This implies that our sense of the universe changing over time and, indeed, the concept of time itself may be an illusion. Time, according to this notion, is an "emergent concept" that arises from a more fundamental reality and seems to exist only within local branches of the multiverse.

Many of the ideas I have discussed are still quite speculative, but it is thrilling that physicists can talk about such big and deep questions based on theoretical progress. Who knows where these explorations will finally lead us? It seems clear, though, that we live in an exciting era in which our scientific explorations reach beyond what we thought to be the entire physical world—our universe—into a potentially limitless realm. SA

MORE TO EXPLORE

Physical Theories, Eternal Inflation, and the Quantum Universe. Yasunori Nomura in *Journal of High Energy Physics,* Vol. 2011, No. 11, Article No. 063; November 2011. Preprint available at **https://arxiv.org/abs/1104.2324**

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FROM OUR ARCHIVES

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