Islands in the Sea

The universe around us may be only one of very, very many. If so, how can we test the existence of other universes?

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You are standing in a grassy field at midnight. Overhead is a breathtaking wash of stars—a hundred, a thousand, ten thousand light years away. All of them, you know, are located in the Milky Way, a single galaxy beyond which lie billions more stars and galaxies. At such moments the sheer volume of the universe can overwhelm the mind.

Now consider the possibility that this enormity of space — the stars, the galaxies, everything we can see with our most powerful telescopes – may just be a tiny grain on a beach that stretches to the horizon in all directions.

Welcome to the multiverse.

As a general concept, multiverses are not new: Carl Sagan admired the ancient Hindu notion that innumerable universes may coexist, going through endless cycles of life and death. Today, however, the idea of the multiverse is neither philosophy nor fiction, but science. In this picture, ours is only one in a staggering host of universes, each of which has different physical characteristics, or "fundamental constants." Nor are these other universes wooly metaphysical places, or concealed in some higher dimension. They are simply too far away for us to see.

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>
> *- Alexander Vilenkin*

To understand this, point your hand at the sky. Now imagine a ray, starting at the tip of your finger and extending upward. Its tip moves out of the solar system, and beyond the Milky Way, through intervening galaxies – one, then ten, then billions of them. The ray points on, extending to the edge of the visible universe, some 46.5 billion light years from earth, to the spherical rim beyond which even a perfect telescope cannot see in any direction. This rim is sometimes called the Cosmic Horizon, because its distance in light years corresponds with the amount of time that has passed since the universe first became transparent to radiation; that is, the earliest moment when any signal could have begun a journey presently terminating at Earth (signals from farther away haven't had time to get here).

The Cosmic Horizon forms our universe's edge – importantly, not because any physical barrier exists there, but because an informational one does. Beyond it lie regions inaccessible to us and causally disconnected from our own.

Call them other universes.

Eternal Inflation

"This is a new picture of the universe that has emerged from developments in cosmology," says Alex Vilenkin from his office at Tufts University, where he directs the Institute of Cosmology. Vilenkin is the recipient of an almost $62,000 grant from FQXi to study probabilities in the multiverse, the vast concatenation of universes beyond our Horizon.

"[The multiverse concept is] based on the theory of inflation, which now has substantial observational support. [Inflation] is a theory of explosive, accelerated expansion in the very early universe, driven by a peculiar form of matter, which is called false vacuum, and that ended 14 billion years ago. That's what we call the Big Bang."

In the Bang, inflationary thinking goes, the region of space-time in which we now find ourselves condensed out of a previous state, in which faster-than-light expansion was the rule. After the condensation, the inflationary epoch was over – at least locally. But this does not mean inflation ended everywhere.

WELCOME TO MULTIVERSE
Alexander Vilenkin

"It follows from the theory that, although this period of inflation ended in our part of the universe, it is still continuing in other parts," Vilenkin says. "So you have this picture of a huge inflating sea, with these islands — like ours — where inflation ended. And the islands are constantly being formed."

The multiverse continues to proliferate, in other words, constantly causing new regions like ours to come into existence, but never exhausting itself. This overall process had a beginning at some point in the past – "a Bigger Bang," to borrow from The Rolling Stones – but it has no conclusion.

"Inflation never ends, in the entire universe," Vilenkin says. "That's why it is called *eternal inflation*."

Pocket Universes

"[The multiverse] is more or less like a tree with growing branches," says Universitat de Baecelona's Jaume Garriga, a member of Vilenkin's research team.

"Some branches stop growing in the process we call thermalization, by which a pocket universe is created at the tip of that branch. But the rate at which new branches are created is much faster, so there are always more and more fresh branches which will give rise to new pocket universes."

Vitaly Vanchurin, a third co-investigator with Vilenkin who works at Ludwig-Maximilians University in Munich, explains further. "Space expands everywhere, but there are some places – some islands within the space-time – which get thermalized. Once it's thermalized, the regular Big Bang cosmology takes place. But it's only in a fraction of the total space-time volume."

Within each of these pockets, each having its own Big Bang, the rules may turn out to be a little different. For example, when physicists examine our universe, they find that the electron – any electron – has a specific mass. Why this mass and no other? The precise figure, derivable by experiment, doesn't seem inevitable: it just happens that electrons have a mass of me, and not 3 me or 10 me. (The universe would be quite a different place if the alternative figures were correct; see the Sidebar.)

Similarly, when cosmologists measure the cosmological constant – a quantity that connotes the energy density of empty space – they find it neither to be the huge number certain quantum field theories predict, nor the other sensible option: zero. Instead, they find a small, but nonzero, number, with no clear explanation why.

"Most of the particle physicists believed that the energy of our vacuum should be strictly zero," says Vilenkin. "It was clear that, if it was not zero, it was such a tiny number that it would be hard to explain."

Enter another brilliant mind: that of physicist Steven Weinberg.

"Steven Weinberg, kind of in an act of desperation, said, Okay . . . maybe the cosmological constant is not some fixed number," Vilenkin says. "Maybe it changes from one part of the universe to another.

"Then he showed that galaxies can exist only if the cosmological constant is sufficiently low. It was a great improvement, because it explained why the cosmological constant may be small." In other words, the cosmological constant may be small – around here.

If there are in fact a huge number of other universes, with a huge number of possible values for the cosmological constant, but galaxies only form in some of them, then the universes with small values for the cosmological constant are the ones where observers will evolve, look around, and wonder why the cosmological constant is so small. This slightly circular argument is known as the Anthropic Principle (see Sidebar).

"I realized you can do better than that," Vilenkin adds, "if you not only ask: what is the value of the cosmological constant which just allows galaxies to form? But you say: the lower it is, the more galaxies you have.

"So you don't expect to find yourself in a marginal region which allows just one galaxy to form. You expect to find yourself in a place that is teeming with galaxies."

The Problem with Strings

Cut now to one of the most vaunted, and bedeviled, scientific theories of modern times: superstrings.

Begun forty years ago as an attempt to explain certain particle interactions, string theory eventually became a widely discussed candidate for the long-sought Theory of Everything, unifying all of physics. As it developed, however, string theorists were disturbed to find the formalism generating strange things.

"For a long time string theorists hoped to derive all the parameters of nature from fundamental physics," Vilenkin says. "But it turns out instead, they realized that the theory has a huge number of solutions, describing a huge number of possible realms with different physics. Different masses of particles, charges, and so forth."

Instead of producing a single, testable picture of how the universe operates, string theory produced distressingly too many. As the number of pictures grew – it currently stands at a jaw-dropping 10^{500} (an immense number without a name; see the Sidebar) – some theorists turned away, troubled by the lack of experimental data and feeling the densely complex math was generating gibberish.

But perhaps, others thought, this seeming weakness was actually a strength. Perhaps the 'string landscape,' as it is called, was describing what really exists: a multiplicity of universes, their number far outstripping the stars in the night sky.

"And now that you combine this with eternal inflation," Vilenkin says, "it turns out that pockets with all these possible properties will necessary be generated."

Simulating Space-Time

But even granting that the eternally inflating multiverse exists; that the string theory describes it; and that all other universes remain permanently concealed outside our Cosmic Horizon; a principled question arises: Can we know anything about these alternate universes from earth?

"I think so, yes," Vilenkin says. "All these different regions that have different values of the constants are beyond our horizon, that's true. So we cannot observe them directly. However, we can make indirect, statistical, predictions."

Such statistical predictions make up Vilenkin's work for his FQXi grant. His team will develop mathematical tools necessary to analyze all possible vacua in the string landscape, to understand the likelihood of fundamental constants such as ours. Vanchurin will also be working out a technique for simulating these different space-times on a computer.

"One of the approaches is to put a measure on all the possible values of the cosmological constant," says Vanchurin. "So if there is a probability distribution of the cosmological constant, and if we prove that it has the peak at around the value that is measured, that would be good evidence showing that's the explanation."

"Since we do not know which vacuum we inhabit, we must assign a probability to the proposition that we inhabit each one of those which is compatible with the information available to us," echoes Garriga. "Later, we may discover that some of those vacua to which we have assigned a non-vanishing probability are ruled out by new data. However, if we keep doing things right and we are using the right measure of probability, we will find out that on average our predictions are in good agreement with the new data.

"Also, that odd facts for which there was no prior explanation start falling into place."

The Probability of Us

Though we can't observe alternate universes, "The idea is that you can use this picture of the multiverse to explain some puzzling features of the part of the universe that we can observe," Vilenkin says. "And to predict some of the features that we have not yet observed."

Vilenkin's book, *Many Worlds in One: The Search for Other Universes*, released last year, examines the implications, "metaphysical" and otherwise, for eternal inflation. They include such mind-bending conclusions as that there is another region (in fact, an infinite number of them) somewhere in the multiverse where an identical version of you is reading this article right now, pausing to consider what it could mean that in an infinite sea, every kind of island exists somewhere.

"Basically that's a consequence of the fact that quantum mechanics says if something has a nonzero probability it will happen necessarily," Vilenkin says. "If it's not forbidden, it's inevitable."

Infinite and Rare

There is no convenient name assigned by mathematicians to 10^{500}. To grasp just how large a number this is, try writing it out longhand: a 1 followed by 500 zeroes.

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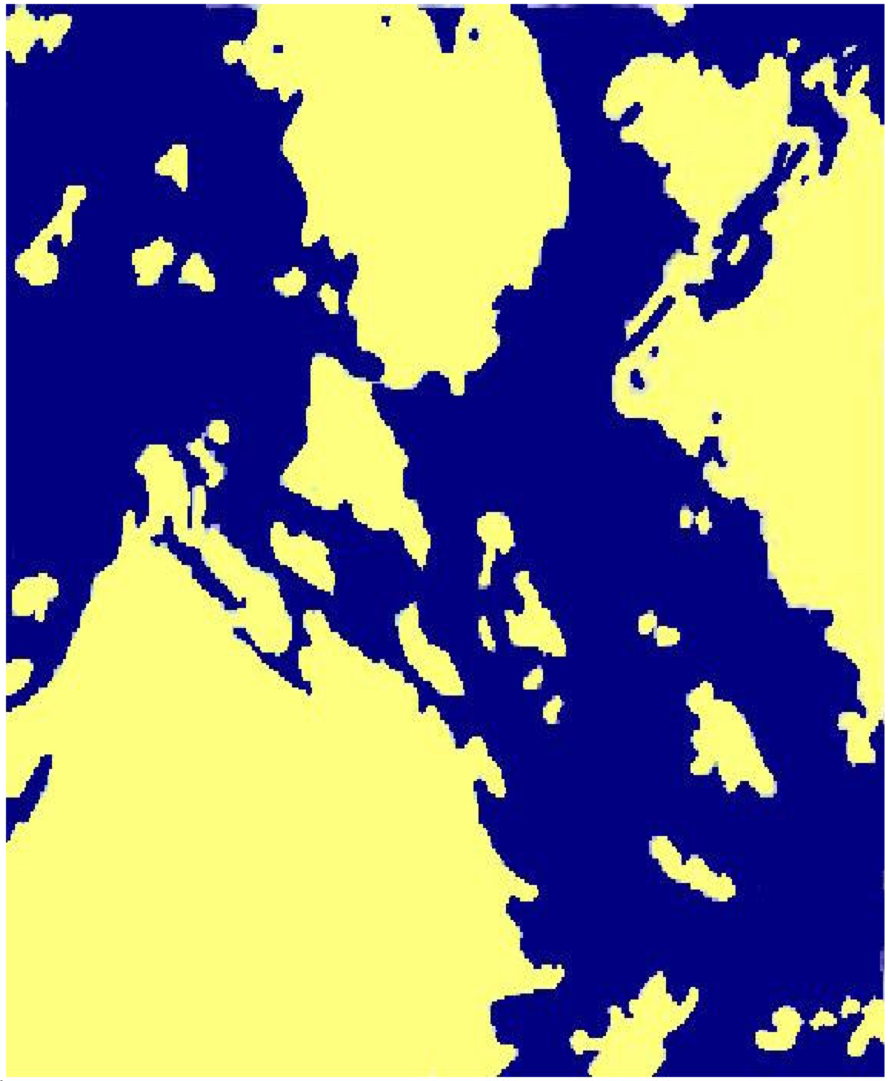
No matter how staggering a figure 10^{500} is, though, it has the same status as any other number. In fact, if the multiverse is infinite, 10^{500} possible vacua do not exhaust it.

"Very large is still finite," says Vanchurin of this strange state of affairs. "So there is a finite number of values, but an infinite number of regions, where those values are realized. If you take each one of those 10^{500}, there are infinitely many places in the multiverse where these values take place."

The vacuum in which we find ourselves — our kind of universe, with its fundamental constants — is thus both fantastically rare, given the possibilities, and also found an infinite number of times. The same is true of every other member of the 10^{500}.



ISLANDS IN THE INFLATING SEA **A computer simulation of eternal inflation.**

The Anthropic Principle

Varying the fundamental constants yields different kinds of universes. If the gravitational constant were much higher, for example, stars would be less massive and would burn out much faster – too fast for intelligent observers to evolve. If protons (of which the atomic nuclei are made) were only one percent more massive, they would decay, causing all atoms to disintegrate. And so on.

Notable among these hypothetical universes is an absence of people. Some theorists have concluded from this absence that the universe is somehow "fine tuned" to bring life into existence, in what is known as the "Strong Anthropic Principle."

Other versions of the principle are more skeptical with regard to human vanity, but nonetheless allow that the apparent connection between the constants and the evolution of life may be partly explained by the fact that life-permitting parameters are the only ones that can be observed.

Think about it: in a universe of nothing but hydrogen gas, no observers would be present to inquire about the absence of fine-tuning.

"It is inevitable to use anthropic selection, but it hardly deserves to be called a principle," Vilenkin says. "If you have a universe with different sorts of regions, some of them allowing the existence of life, then it's clear that an observer will be much more likely to be in one kind of region than another."

"'Selection effect' is the politically correct denomination for what used to be called the Weak Anthropic Principle," Garriga says. "Physicists were once reluctant to account for the bias introduced by the necessity of a physical observer. This is understandable. It would be better if we could make sharp predictions based on, say, the mathematical consistency of the theory.

"However, we know that the distance from the sun to the earth cannot be derived from the mathematical consistency of the earth's orbit around the sun. Likewise, in a theory with a vast landscape of vacua, we may have to resort to probabilistic descriptions of what we should expect, and in this context the anthropic bias should be accounted for."

Those who still want the Strong Anthropic Principle to pan out at least have some consolation: in a multiverse, there are an infinite number of people who feel that way.