A radical new interpretation of string theory raises the prospect of untold numbers of separate universes with different physical laws—an idea that some physicists say threatens the foundation of their science

A 'Landscape' Too Far?

NEWPORT BEACH, CALIFORNIA—Physicists have long heaped scorn on anyone who tried to explain features of the universe by pointing out that had they been otherwise, life would be impossible.

This "anthropic principle," many physicists charged, abandoned the long-standing goal of finding equations that specify all of nature's properties. Most preferred the notion that a comprehensive theory would account for everything the universe has to offer.

Ironically, however, the favored candidate for that approach—superstring theory—may be exacerbating the very problem everybody hoped it would solve. Far from disposing of anthropic reasoning, string theory has reinvigorated its advocates, leading to a philosophical schism within the physics community.

The dispute has touched off sharp exchanges both within and outside science journals. In January, for example, experimental physicist and Nobel laureate Burton Richter of Stanford University in Palo Alto, California published a letter in the *New York Times Book Review* blasting the anthropic approach as sterile and unscientific. Its proponents "have given up," he wrote. "I can't understand why they don't take up something else—macramé, for example." Another Nobel laureate, David Gross of the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara (UCSB), compares anthropic thinking to a disease. "I inoculate myself by emotional intensity against it because it's very contagious," he says.

> **"I inoculate myself by emotional intensity against [this idea],** because it's very contagious."
>
> —David Gross, UC Santa Barbara

On the other hand, Stanford University physicist Leonard Susskind believes that anthropic reasoning may be the wave of physics' future. Susskind is a leading advocate of a new view of reality called the superstring landscape, in which the known universe is just a tiny habitable corner of a grander reality. If the landscape idea is correct, string theory offers no specific predictions about the universe's properties but rather implies the possible existence of a countless number of combinations of properties—like a vast landscape with differing physical features.

In the landscape scenario, life can exist only where the mix of properties leads to a hospitable environment—precisely the sort of reasoning long used by advocates of the anthropic principle. So the string landscape has emboldened many supporters and even converted some skeptics into saying the a-word aloud—much to the dismay of its die-hard opponents.

During a panel discussion at a recent physics conference here,* Richter recited a blistering indictment of the landscape and its anthropic implications. "The anthropic

* 14th International Conference on Supersymmetry and the Unification of Fundamental Interactions, 12–17 June.

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principle is an observation, not an explanation," he declared. "The landscape, as far as I can see, is pretty empty. … It looks to me that much of what passes for theory these days is more like theological speculation."

Views like those expressed by Richter and Gross have dominated physics for decades, with anthropic reasoning relegated mostly to pub discussions and the occasional popular book. But that began to change around the turn of the millennium, when the supposed cure for anthropic reasoning—superstring theory—suddenly began to spread the disease.

Throughout the 1980s and '90s, superstring theory was frequently advertised as potentially being the ultimate "theory of everything." By conceiving basic bits of matter as loops or snippets of string, rather than tiny points, superstring theory offered the prospect of merging general relativity and quantum mechanics into a consistent framework. Its supporters hopefully predicted that the final version of string theory would precisely specify all of nature's features as natural outcomes of some master equations.

But in 2000, Joseph Polchinski of UCSB and Raphael Bousso, now at UC Berkeley, published a landmark paper in the *Journal of High Energy Physics* (*JHEP*) that put the landscape on the string-theory map. Technically, they showed that the theory permits a huge number of different metastable vacuum states—that is, spaces that could exist for a long time with a vast range of physical properties, such as the masses of basic particles and the density of energy in the vacuum of space.

For years, theorists have struggled in vain to calculate the density of the vacuum energy, now known commonly as the "dark energy" thought to be driving the universe's accelerating expansion. But their calculations give an answer that is too high by something between 10^{60} and 10^{120} orders of magnitude.

If the string landscape exists, however, the problem is moot. In the landscape, the vacuum energy can take on all sorts of possible values. If there is no one right answer for the vacuum energy's value, that could explain why no theory could predict what it is. Physicists are around to ponder the issue only in a space where the vacuum energy's value permits life to exist.

In the landscape story, the local amount of vacuum energy is an environmental accident that happens to permit life's existence rather than a natural outcome of basic laws of physics. But determining

"Much of what passes for theory these days is **more like theological speculation."**

—Burton Richter, Stanford University

what is "natural" in physics is itself a contentious issue. At the Newport Beach conference, a panel session convened to discuss "naturalness" became a forum for debating anthropic reasoning.

Susskind pointed out that the string landscape meshes nicely with developments in big bang cosmology since the early 1980s, when Alan Guth, Andrei Linde, and others developed the theory of inflation. In that view, a tiny patch of space burst suddenly larger in a brief instant of inflationary expansion; the newborn universe then continued expanding at a more leisurely pace to produce the mature universe observed today. Satellite observations have provided strong support for inflation's predictions about features imprinted in the cold glow of microwaves left over from the big bang.

If the inflationary origin of the known universe is correct, the same process could have happened over and over again, with new "bubble" universes forming within old ones ad infinitum—a scenario known as eternal inflation. In the early 1980s, Linde, Soviet physicist Andrei Sakharov, and others pointed out that the resulting "multiverse" of bubbles might explain certain mysteries anthropically. Each bubble might have a different density of vacuum energy, some very high. But a large vacuum energy makes galaxy formation (and hence stars, planets, and people) impossible. Our bubble must therefore have a small vacuum energy—possibly zero—in order for life to exist.

In 1987, that argument was made more precise by Steven Weinberg of the University of Texas, Austin, another Nobel physics laureate. Weinberg showed that the existence of life did not require that the vacuum energy be zero, only that it be much smaller than physicists had calculated. About a decade later, evidence for cosmic acceleration bore out the prediction of nonzero vacuum energy in our universe.

Most string theorists initially ignored the discovery of vacuum energy—or assumed their theory would eventually explain its magnitude, whatever it was. Around that time, Polchinski began discussions with Bousso about string theory's relation to cosmology. By 2000, they had produced the *JHEP* paper suggesting that string theory itself forecast an incredible number of possible vacuum states (by current estimates, perhaps as many as 10^{500}, or even more).

Adversaries. In a panel discussion on the nature of physical law, theoretical physicists Andrei Linde (*left*) and Burton Richter disagreed sharply about the status of the "string-theory landscape."

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A Reluctant Convert

Like most physicists, Joseph Polchinski never much liked the idea that the existence of life had anything to do with the nature of the universe.

The so-called anthropic principle—that properties of the universe were somehow inexplicably hospitable for the evolution of life—smelled too much like metaphysical mush. Physics was supposed to find equations that answered basic questions about the cosmos, such as how much energy resided in the vacuum of space.

But the equations predicted far too much vacuum energy to allow the formation of galaxies or any conceivable habitat for life. So most physicists thought there simply was no such energy—that the vacuum energy, technically known as the cosmological constant, was zero. If it were not zero, but still small enough to allow life, it would be hard to see how to explain it with equations. In fact, Polchinski told cosmologist Sean Carroll a decade ago, if astronomers ever found evidence for a nonzero cosmological constant, he'd give up physics—because that would signal the need to invoke the anthropic principle.

Changed man. Joseph Polchinski once told a colleague he'd quit physics rather than invoke the anthropic principle.

Such a vast repertoire of possible universes emerged from the many convoluted ways in which the objects of string theory can twist themselves up. String theory's hallmark (and to some, most horrifying) feature is its need for six or seven extra dimensions of space beyond the three dimensions of ordinary experience. One-dimensional strings vibrate within this higher dimensional space, with different modes of vibration corresponding to different kinds of particles. Other objects can exist, such as two-dimensional "membranes" and other "branes" of higher dimension. String theory analogs of magnetic fields (called fluxes) can emanate from the branes. And string theory's multiple dimensions fold up on themselves in thousands of configurations containing spacetime gaps (or handles) sort of like the hole in a doughnut. The universe's physical properties depend on the resulting arrangement of the strings, branes, fluxes, and handles, and they can assume a nearly countless number of configurations. Just as protons, neutrons, and electrons can combine to produce hundreds of atoms and thousands of molecules, Polchinski says, branes, handles, and fluxes can produce a vast number of different species of spacetime.

At first, many physicists dismissed string-landscape vacuums as quirks of the math with no relation to reality. But in 2003, a paper by Linde, of Stanford, and three collaborators (Shamit Kachru, Renata Kallosh, and Sandip Trivedi) published in *Physical Review D* showed that the many vacuums in the landscape might actually exist, at least long enough to give rise to life.

Since then, the landscape concept has generated a burgeoning bibliography of papers along with relentless antianthropic animosity. Anthropic explanations "are fun parlor games," says Gross, director of the Kavli Institute for Theoretical Physics at UCSB. "But they're not science in the usual sense of making predictions that can be tested to better and better precision over the years."

Gross fears that anthropic infections might incapacitate attempts to find unique answers to tough questions by inducing people to give up the quest. He cites historical examples in which seemingly incalculable features of nature—say, the spacing of energy levels in atomic nuclei—eventually yielded to reductionist explanation. In fact, he emphasizes, nearly all the normal, observable world can in principle be explained by the standard model of physics without resorting to any anthropic considerations. "Most people have absolutely no idea how successful science has been at explaining, with one or two parameters, all of the physics that they know of in everyday life," he said.

Richter expresses similar sentiments. "I don't see any problem with part of the theory community going off into a metaphysical wonderland, but I worry that it may be leading too many of the young theorists into the same thing," he says.

Landscape advocates reject such criticisms, contending that opposition to anthropic reasoning is largely emotional. "There's no substantive scientific debate," Susskind says. "The nature of what is going on is different emotional reactions to some facts and some interpretations of those facts that we've discovered." And those facts suggest that the universe is vastly larger than what scientists can see.

"We no longer have any evidence that our little piece of the universe is representative of the whole thing," Susskind argues. And if the universe is not everywhere the same, then the properties of nature that physics has tried to specify would differ from place to place. "Once we agree that it's diverse, then some features of it are environmental," he says. "We have to figure out which ones."

But that doesn't mean that physics must abandon the goal of making testable predictions. "We're all struggling quite hard to make observational physics out of it," Susskind says. And Linde points out that future observations of gravitational waves from the early universe could falsify, or verify, anthropic predictions about the nature of spacetime curvature predicted on anthropic grounds.

"It's science," Linde asserted during the Newport Beach panel discussion. "It's not science fiction. It's not religion. … It's something where we can really use our knowledge of mathematics and physics and cosmology." Far from taking the easy way out, as its opponents sometimes allege, anthropic science is depressingly difficult, he observed. "It's complicated. It's not an easy job to do, so if you don't

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As a leading superstring theorist, Polchinski, of the Kavli Institute for Theoretical Physics at the University of California (UC), Santa Barbara, was in the thick of the fight to find the ultimate equations describing reality, the somewhat mislabeled "theory of everything" that should have unified gravity with nature's other forces. "People in string theory were very fixed on the idea that there was some powerful mathematical structure we hadn't fully identified, and when we did, we would know why the cosmological constant was exactly zero," recalls Polchinski.

Even in 1997, when astronomers reported evidence for a nonzero cosmological constant, "very few string theorists either knew or wanted to admit the significance of it in terms of the anthropic principle," Polchinski says.

Neither did Polchinski himself. But shortly thereafter, he began a collaboration with Raphael Bousso, now at UC Berkeley, that led to a shocking result: String theory itself predicted numerous possible vacuum states with different values for the cosmological constant. Dismayed by the anthropic implications, Polchinski was reluctant to publish the results, but Bousso insisted. "We totally agreed on the science," Polchinski says, "but he was the one who really said, 'Look, we've got to publish this.' "

After the paper was published in the *Journal of High Energy Physics* in 2000, Polchinski remained in quasi-denial, unwilling to embrace the anthropic "dark side" of physics. But the paper inspired others to investigate what came to be called the "landscape" of vacuum-state possibilities. Most outspoken among them was Leonard Susskind of Stanford University in Palo Alto, California.

"Lenny came along and said, 'Look, we can't sweep this under the rug; we have to take this seriously,' " Polchinski says. "If this is the way things are, science is only going to move forward by thinking about it, not by pretending it's not there."

However reluctantly, Polchinski has now become an anthropic advocate of sorts. His tipping point, he says, came at a dinner for donors to the Kavli Institute. One attendee asked about the anthropic principle.

"And I said nobody believes that," Polchinski recalls. "And when I said that, I knew I was lying. I knew that the evidence was mounting for the anthropic principle."

So 2 years after the landscape paper appeared, Polchinski delivered his first talk on the topic, describing the landscape and acknowledging its anthropic implications at a conference in Chicago, Illinois. Carroll, of the University of Chicago, was there, Polchinski remembers: "He immediately said, 'Can I have your desk?' "

–T.S.

want to do it, then don't do it. But don't say that it's not science."

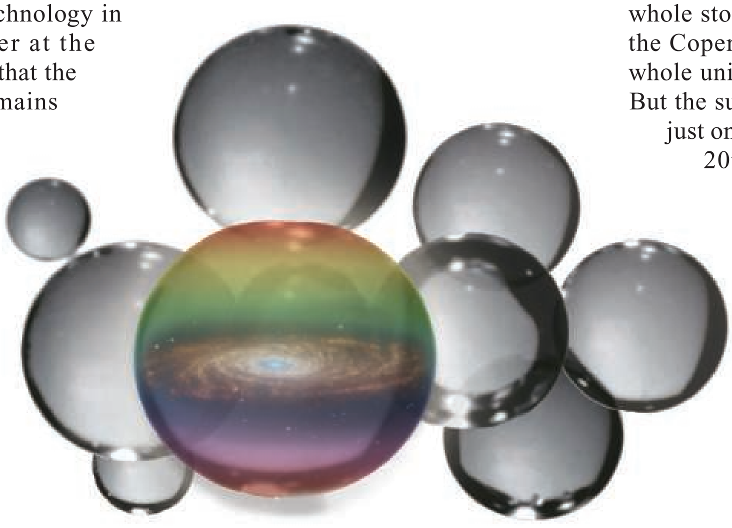
Other physicists, although reluctant to embrace anthropic reasoning, decry the acrimony and seek a middle ground. "It's unfortunate that it has turned into a situation where you have to choose to be in one camp or the other," says Clifford Johnson, a string theorist at the University of Southern California in Los Angeles. "It would be nice if we could explore some of those unpalatable ideas just in case that's the way that nature chooses to go."

Of course, it's possible that the landscape will turn out to be wrong. "It may well be that further understanding of string theory will show that the multiple possible spacetime vacuums are just phantoms," Johnson says.

Nobel laureate Frank Wilczek of the Massachusetts Institute of Technology in Cambridge, another speaker at the Newport Beach panel, agrees that the fate of the landscape idea remains uncertain. "I don't think the landscape is established to any convincing level of rigor," he says. "There are lots of shaky aspects to the argument."

In fact, technical objections to the reality of the landscape have been raised, notably by Tom Banks of UC Santa Cruz. And recent work by Paul Steinhardt of Princeton University and Neil Turok of Cambridge University in the U.K. suggests that the vacuum-energy problem can be explained "naturally," without anthropic reasoning, if the universe undergoes a cyclic repetition of expansion and collapse. Recent work by Stephen Hawking of Cambridge University and his collaborator Thomas Hertog of CERN, the European particle physics laboratory near Geneva, Switzerland, suggests that rather than describing a multiverse of spacetime bubbles, the landscape reflects alternative realities embodied in the equations of quantum mechanics. Under Hawking and Hertog's assumptions, only a few of the landscape's realities have a significant probability of actually existing.

"It's not an easy job to do, so if you don't want to do it, then don't do it. **But don't say that it's not science."**
—Andrei Linde, Stanford University



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Given the current state of knowledge, efforts to either confirm or refute the landscape's anthropic implications are simply premature, says cosmologist Sean Carroll of the University of Chicago in Illinois, who will soon be moving to the California Institute of Technology in Pasadena. But, he says, the idea that the known universe is only a small part of something much bigger should not come as so much of a shock. "Again and again in the history of cosmology, we've been shown that the little pieces we've been looking at are not the whole story," Carroll says. At the time of the Copernican revolution, the supposed whole universe was just the solar system. But the sun eventually was revealed to be just one star in a vast galaxy, and in the 20th century, that galaxy became just one speck in space among billions and billions of others.

As Wilczek observes, the string landscape and the multiverse merely suggest that the same story is happening again. "This is going one step further," he says. "We should be used to it by now."

–TOM SIEGFRIED

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