COSMOLOGY

Bad Boy of Physics

Leonard Susskind rebelled as a teen and never stopped. Today he insists that reality may forever be beyond reach of our understanding

Interview by Peter Byrne

STANFORD UNIVERSITY PHYSICIST LEONARD SUSSKIND REVELS IN DISCOVERING IDEAS that transform the status quo in physics. Forty years ago he co-founded string theory, which was initially derided but eventually became the leading candidate for a unified theory of nature. For years he disputed Stephen Hawking's conjecture that black holes do not merely swallow objects but grind them up beyond recovery, in violation of quantum mechanics. Hawking eventually conceded. And he helped to develop the modern conception of parallel universes, based on what he dubbed the "landscape" of string theory. It spoiled physicists' dream to explain the universe as the unique outcome of basic principles.

Physicists seeking to understand the deepest levels of reality now work within a framework largely of Susskind's making. But a funny thing has happened along the way. Susskind now wonders whether physicists *can* understand reality.

IN BRIEF

WHO
LEONARD SUSSKIND

VOCATION | AVOCATION
Theoretical physicist, known especially for pioneering string theory, black hole physics and the multiverse

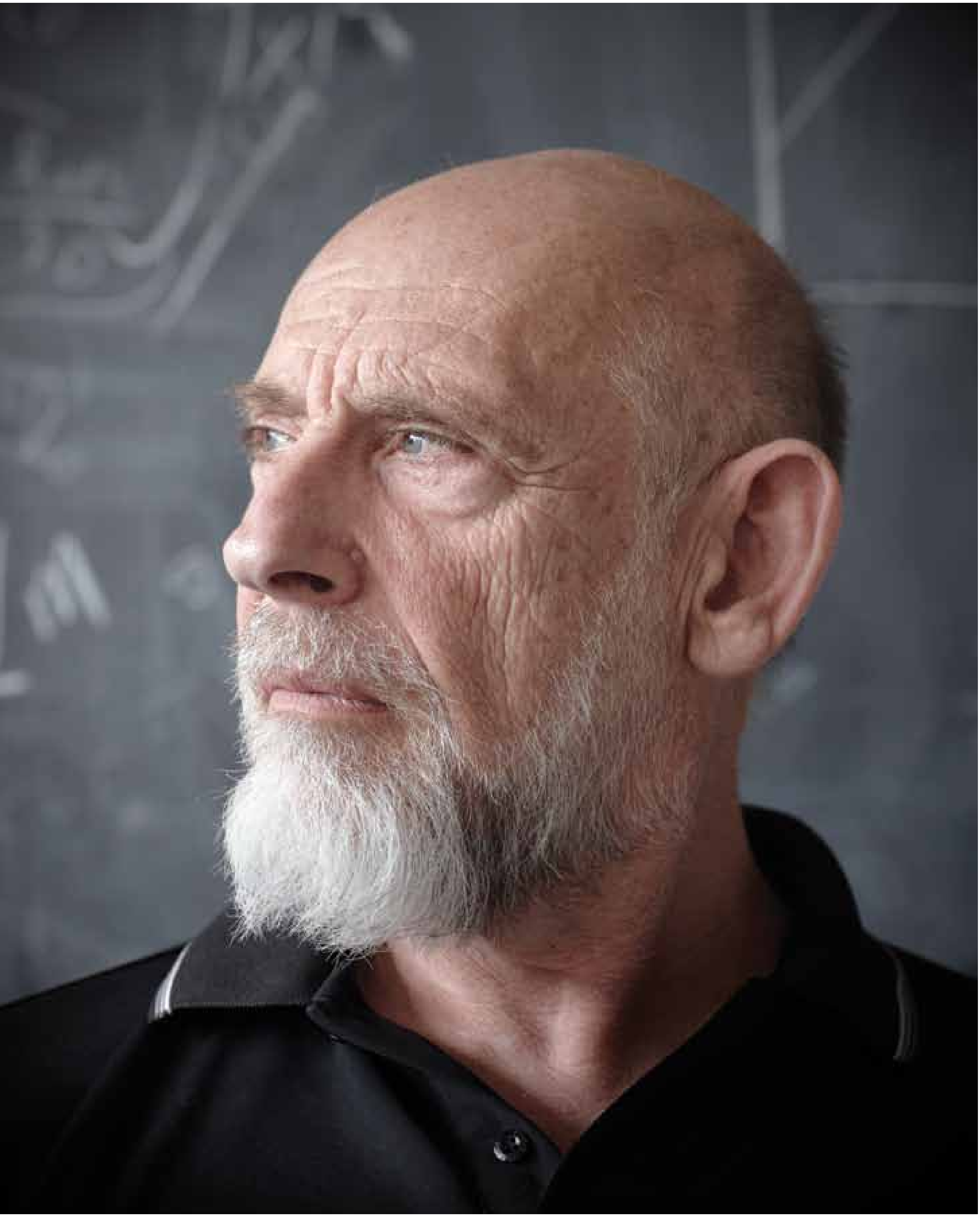
WHERE
Stanford University

RESEARCH FOCUS
What is the deep nature of physical reality?

BIG PICTURE
We may never be able to grasp that reality. The universe and its ingredients may be impossible to describe unambiguously.

Susskind worries that reality might be beyond our limited capacity to visualize it. He is not the first to express such a concern. In the 1920s and 1930s the founders of quantum mechanics split into realist and antirealist camps. Albert Einstein and other realists held that the whole point of physics is to come up with some mental picture, however imperfect, of what objective reality is. Antirealists such as Niels Bohr said those mental images are fraught with peril; scientists should confine themselves to making and testing empirical predictions. Susskind thinks the contradictions and paradoxes of modern physics vindicate Bohr's wariness.

One thing that led Susskind to this conclusion is his principle of black hole complementarity, which holds that there is an inherent ambiguity in the fate of objects that fall into a black hole. From the point of view of the falling object itself, it passes without incident through the hole's perimeter, or ho-



Photograph by Timothy Archibald

rizon, and is destroyed when it reaches the hole's center, or singularity. But from the vantage point of an external observer, the falling object is incinerated at the horizon. So what really happens? The question, according to the principle of black hole complementarity, is meaningless: both interpretations are valid.

A related idea favoring antirealism is the holographic principle that Susskind and Nobel laureate Gerard 't Hooft of Utrecht University formulated in the mid-1990s. It holds that what happens in any volume of spacetime can be explained by what happens on its boundary. Although we usually think of objects as zipping around three-dimensional space, we can equally well think of them as flattened blobs sliding across a two-dimensional surface. So which is the true reality: the boundary or the interior? The theory does not say. Reality, in this holographic conjecture, is perspectival.

Hoping to better understand how the tension between hard evidence and unproved conjecture works at the frontier of physics, we asked Susskind to explain how his ideas have evolved.

Scientific American: How did the son of a Bronx plumber end up questioning the nature of reality?

LEONARD SUSSKIND: I was a bad high school student. I was very good in mathematics, but I was a bad boy, and I got in trouble a lot. The effect of that is I wasn't allowed to take regular physics. I was told I had to take automotive physics. But then in college, which was an engineering school, I took my first physics course. I was just so much better than anybody else, including the professor. And fortunately, it was not a source of contention between us that I could do the things he couldn't. But then I was actually told by one of the engineering professors that he didn't think I was cut out to be an engineer, which was correct. I asked him, "What should I do?" He said, "Well, you're exceptionally smart. You should become a scientist."

Did you take any philosophy courses?

Yeah, I did in college. I was quite fascinated by some of the concepts. My interest in it lapsed when I really got hooked by physics.

Are there any philosophers of science whom you like?

I'm one of the few physicists I know who likes Thomas Kuhn. He was partly a historian of science, partly a sociologist. He got the basic idea right of what happens when the scientific paradigm shifts. A radical change of perspective suddenly occurs. Wholly new ideas, concepts, abstractions and pictures become relevant. Relativity was a big paradigm shift. Quantum mechanics was a big paradigm shift. So we keep on inventing new realisms. They never completely replace the old ideas, but they do largely replace them with concepts that work better, that describe nature better, that are often very unfamiliar, that make people question what is meant by "reality." Then the next thing comes along and turns that on its head. And we are always surprised that the old ways of thinking, the wiring that we have or the mathematical wiring that we may have created, simply fail us.

In the midst of all this remodeling, is there room for such a thing as an objective reality?

Every physicist must have some sense that there are objective things in the world and that it's our job to go and find out what those objective things are. I don't think you could do that without having a sense that there is an objective reality. The evidence for objectivity is that experiments are reproducible. If you kick a rock once, you'll hurt your toe. If you kick a rock twice, you'll hurt your toe twice. Do the same experiment over and over with a rock, and you'll reproduce the same effect.

That said, physicists almost never talk about reality. The problem is that what people tend to mean by "reality" has more to do with biology and evolution and with our hardwiring and our neural architecture than it has to do with physics itself. We're prisoners of our own neural architecture. We can visualize some things. We can't visualize other things.

Einstein's abstract, four-dimensional geometry was hard to concretely visualize. It became visualizable through mathematical relations. When relativity suddenly appeared, it must have seemed to many people: What happened to "real" time? What happened to "real" space? It just got mixed up into this funny thing, but there were rules. The point was there were clear and precise mathematical rules that had been abstracted out of it, and these survived, and the old notions of reality went away.

So I say, let's get rid of the word "reality." Let's have our whole discussion without the word "reality." It gets in the way. It conjures up things that are rarely helpful. The word "reproducible" is a more useful word than "real."

What about quantum mechanics? According to that theory, kicking the same rock the same way can actually give different results.

That's the big one, isn't it? There are two things that were discovered in quantum mechanics that upset our classical sense of reality. One was entanglement. What entanglement said was something very bizarre: that you can know everything there is to know about a composite system and yet not know everything about the individual constituents. It is a good example of how we're simply not biologically equipped for abstraction and how our sense of reality gets upset [see "Living in a Quantum World," by Vlatko Vedral; Scientific American, June].

The other thing that really hit hard on the idea of classical reality was the Heisenberg uncertainty principle. If you try to describe an object as having both a position and a momentum, you'll run into trouble. You should think of it as having a position or a momentum. Don't try to do both.

This is what physicists mean by "complementary"?

Exactly. It turns out that the mathematics of the event horizon of a black hole is very similar to the uncertainty principle. Again, it's a question of "or" versus "and." At a completely classical level something falls into a black hole, something doesn't fall into a black hole, whatever. There are things outside the black hole, and there are things inside the black hole. What we learned is that's the wrong way to think. Don't try to think of things happening outside the horizon and things happening inside the horizon. They're redun-

Black holes reveal the limits of our capacity to understand the universe.

DON DIXON

dant descriptions of the same thing. You describe it one way, or you describe it the other way. This means we have to give up the old idea that a bit of information is in a definite place [see "Black Holes and the Information Paradox," by Leonard Susskind; Scientific American, April 1997].

If I get you correctly, the holographic principle extends the complementary model of a black hole to the universe.
Yes. Suppose we want to describe some system with enormous precision. To probe with great precision, you need high energy. What's eventually going to happen as you try to get more and more precise is you're going to start creating black holes. The information in a black hole is all on the surface of the black hole. So the more and more refined description you make of a system, you will wind up placing the information at a boundary.

There are two descriptions of reality: either reality is the bulk of spacetime surrounded by the boundary, or reality is the area of the boundary. So which description is real? There is no way to answer that. We can either think of an object as an object in the bulk space or think of it as a complicated, scrambled collection of information on the boundary that surrounds it. Not both. One or the other. It's an incredibly scrambled mapping of one thing to the other thing.

The original goal of string theory was to provide a unique explanation of reality. Now it gives us multiple universes. What happened?
A large fraction of the physics community has abandoned trying to explain our world as unique, as mathematically the only possible world. Right now the multiverse is the only game in town. Not everybody is working on it, but there is no coherent, sharp argument against it.

In 1974 I had an interesting experience about how scientific consensus forms. People were working on the as yet untested theory of hadrons [subatomic particles such as protons and neutrons], which is called quantum chromodynamics, or QCD. At a physics conference I asked, "You people, I want to know your belief about the probability that QCD is the right theory of hadrons." I took a poll. Nobody gave it more than 5 percent. Then I asked, "What are you working on?" QCD, QCD, QCD. They were all working on QCD. The consensus was formed, but for some odd reason, people wanted to show their skeptical side. They wanted to be hard-nosed. There's an element of the same thing around the multiverse idea. A lot of physicists don't want to simply fess up and say, "Look, we don't know any other alternative."

The universe is very, very big. Empirically we know it's at least 1,000 times bigger in volume than the portion that we can ever see. The success of the concept of cosmic inflation opens the possibility that the universe is varied on big-enough scales. String theory provides Tinkertoy elements that can be put together in an enormous number of ways. So there's no point in looking for explanations of why our piece of the world is exactly the way it is because there are other pieces of the world that are not exactly the same as ours. There can't be a universal explanation of everything that it is any more than there can be a theorem that says the average temperature of a planet is 60 degrees Fahrenheit. Anyone who tried to make a calculation to prove that planets have a temperature of 60 degrees would be foolish because there are lots of planets out there that don't have that temperature.

But nobody knows the underlying rules for multiverses. It's a picture. Nobody knows how to use this predictively. This process of eternal inflation just produces bubble after bubble after bubble and produces any number of them of every kind. So that means that the probability for one versus the other is infinity over infinity. We would like to have a probability distribution that would say one is more probable than the other and then make a prediction. So we've gone from what looks like a very compelling picture on the one hand to absurdly trying to measure an infinity of probabilities. If it's going to go down, it's going to go down because of that [see "The Inflation Debate," by Paul J. Steinhardt; Scientific American, April].

Is it possible to do theoretical physics and not have philosophical thoughts?
Most great physicists have had a fairly strong philosophical side. My friend Dick Feynman hated philosophy and hated philosophers, but I knew him well, and there was a deep philosophical side to him. The problems that you choose to think about are conditioned by your philosophical predispositions. But I also have a strong sense that surprises happen and put your philosophical prejudices on their head. People have the idea that there are cut-and-dried rules of science: you do experiments, you get results, you interpret them; in the end, you have something. But the actual process of science is as human and as chaotic and as contentious as anything else. SA

Peter Byrne *is author of "The Many Worlds of Hugh Everett" in the December 2007 issue of* Scientific American, *which developed into the book* The Many Worlds of Hugh Everett III: Multiple Universes, Mutual Assured Destruction and the Meltdown of a Nuclear Family *(Oxford University Press, 2010).*

MORE TO EXPLORE

Farewell to Reason. Paul Feyerabend. Verso, 1988.
The Cosmic Landscape: String Theory and the Illusion of Intelligent Design. Leonard Susskind. Back Bay Books, 2006.
The Black Hole War: My Battle with Stephen Hawking to Make the World Safe for Quantum Mechanics. Leonard Susskind. Back Bay Books, 2009.

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