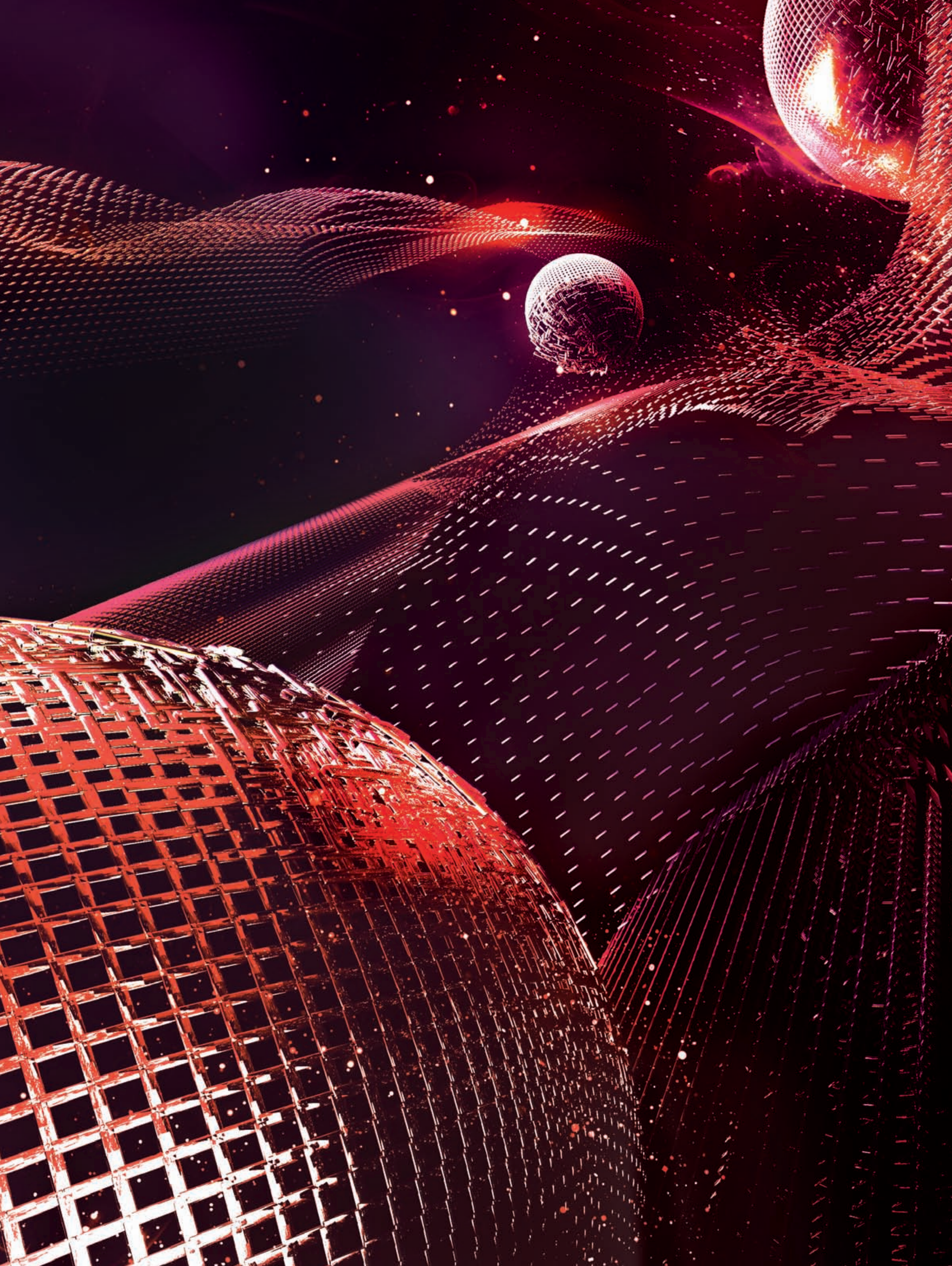


EXPERIMENTAL PHYSICS

IS SPACE DIGITAL?

An experiment going up outside of Chicago will attempt to measure the intimate connections among information, matter and spacetime. If it works, it could rewrite the rules for 21st-century physics

By Michael Moyer

Illustration by Vault49

CRAIG HOGAN BELIEVES THAT THE WORLD IS FUZZY. THIS IS NOT A METAPHOR. HOGAN, A physicist at the University of Chicago and director of the Fermilab Particle Astrophysics Center near Batavia, Ill., thinks that if we were to peer down at the tiniest subdivisions of space and time, we would find a universe filled with an intrinsic jitter, the busy hum of static. This hum comes not from particles bouncing in and out of being or other kinds of quantum froth that physicists have argued about in the past. Rather Hogan's noise would come about if space was not, as we have long assumed, smooth and continuous, a glassy backdrop to the dance of fields and particles. Hogan's noise arises if space is made of chunks. Blocks. Bits. Hogan's noise would imply that the universe is digital.

It is a breezy, early autumn afternoon when Hogan takes me to see the machine he is building to pick out this noise. A bright-blue shed rises out of the khaki prairie of the Fermilab campus, the only sign of new construction at this nearly half-century-old facility. A fist-wide pipe runs 40 meters from the shed to a long, perpendicular bunker, the former home of a beam that for decades shot subatomic particles north toward Minnesota. The bunker has been reclaimed by what Hogan calls his Holometer, a device designed to amplify the jitter in the fabric of space.

He pulls out a thick piece of sidewalk chalk and begins to write on the side of the cerulean shed, his impromptu lecture detailing how a few lasers bouncing through the tubes can amplify the fine-grain structure of space. He begins by explaining how the two most successful theories of the 20th century—quantum mechanics and general relativity—cannot possibly be reconciled. At the smallest scales, both break down into gibberish. Yet this same scale seems to be special for another reason: it happens to be intimately connected to the science of information—the 0's and 1's of the universe. Physicists have, over the past couple of decades, uncovered profound insights into how the universe stores information—even going so far as to suggest that information, not matter and energy, constitutes the most basic unit of existence. Information rides on tiny bits; from these bits comes the cosmos.

If we take this line of thinking seriously, Hogan says, we should be able to measure the digital noise of space. Thus, he has devised an experiment to explore the buzzing at the universe's most fundamental scales. He will be the first to tell you that it might not work—that he may see nothing at all. His effort is an experiment in the truest sense—a trial, a probe into the unknown. "You cannot take the well-tested physics of spacetime and the well-tested physics of quantum mechanics and calculate what we'll see," Hogan says. "But to me, that's the reason to do the experiment—to go in and see."

And if he does see this jitter? Space and time are not what we thought. "It changes the architecture of physics," Hogan says.

FOR MANY YEARS PARTICLE PHYSICS HAS NOT OPERATED on this sort of exploratory model. Scientists spent the late 1960s and early 1970s developing a web of theories and insights that we now know as the Standard Model of particle physics. In the decades since, experiments have tested it with increasing depth and precision. "The pattern has been that the theory community has come up with an idea—for example, the Higgs boson—and you have a model. And the model makes a prediction, and the experiment rules it out or not," Hogan says. Theory comes first, experiments later.

This conservatism exists for a very good reason: particle physics experiments can be outrageously expensive. The Large Hadron Collider (LHC) at CERN near Geneva required around $5 billion to assemble and currently occupies the attention of thousands of physicists around the world. It is the most sophisticated, complex and precise machine ever built. Scientists openly wonder if the next generation of particle collider—at higher energies, larger sizes and greater expenses—will prove too ambitious. Humanity may simply refuse to pay for it.

IN BRIEF

Space may not be smooth and continuous. Instead it may be digital, composed of tiny bits. Physicists have assumed that these bits are far too small to measure with current technology.

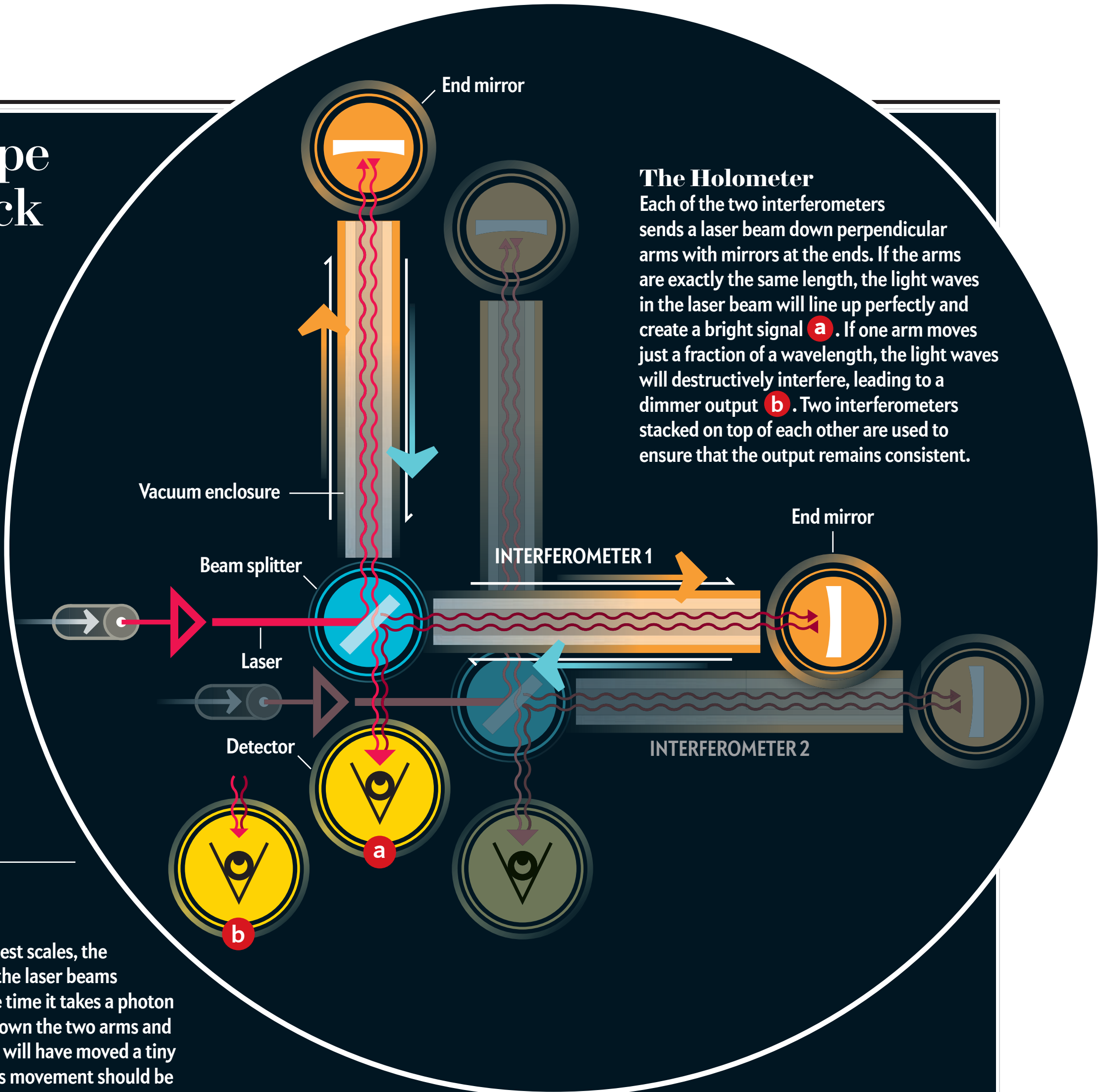
Yet one scientist thinks that he has devised a way to detect the bitlike structure of space. His machine—at present under construction—will attempt to measure its grainy nature.

The experiment is one of the first to investigate the principle that the universe emerges from information—specifically, information that is imprinted on two-dimensional sheets.

If successful, the experiment will shift the foundations of what we know about space and time, providing a glimpse of a new physics that could supplant our existing understanding.

A Microscope to the Planck Length

With his Holometer, Craig Hogan will try to measure a fundamental jitter in spacetime at the smallest scale. The device consists of two interferometers, instruments that amplify very small changes in distance (*right*). Detecting a jitter would indicate that spacetime is digital—divided into discrete packets (*bottom*).

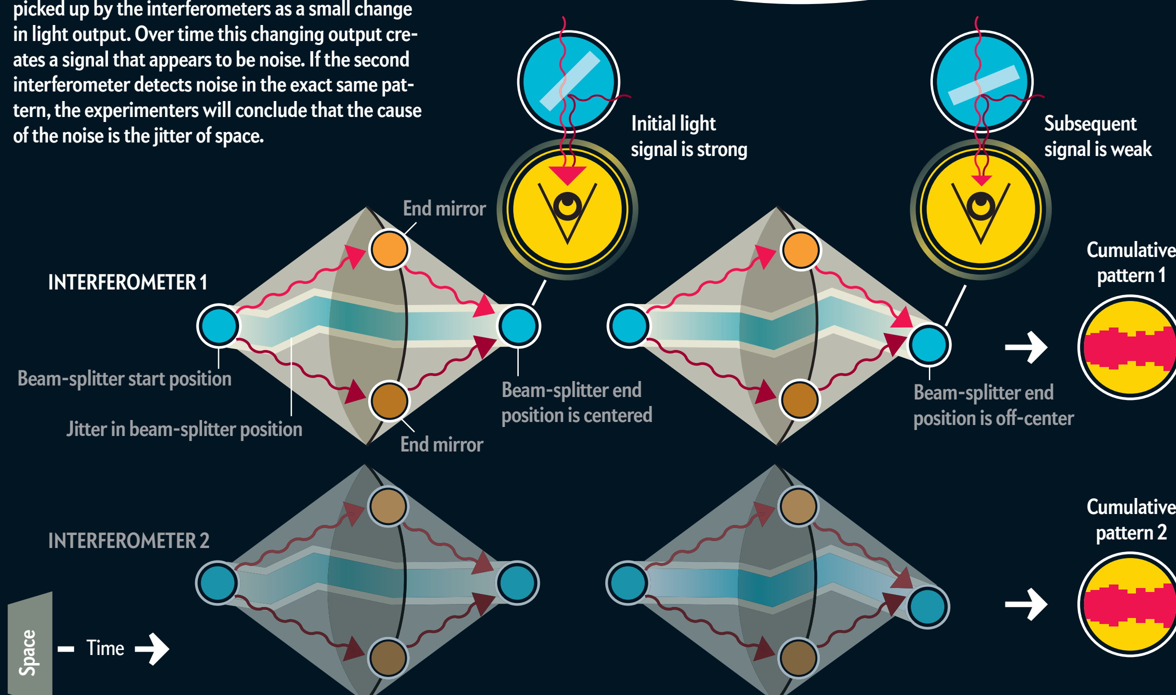


The Holometer

Each of the two interferometers sends a laser beam down perpendicular arms with mirrors at the ends. If the arms are exactly the same length, the light waves in the laser beam will line up perfectly and create a bright signal (a). If one arm moves just a fraction of a wavelength, the light waves will destructively interfere, leading to a dimmer output (b). Two interferometers stacked on top of each other are used to ensure that the output remains consistent.

The Jitter of Space

If space is frothy on the smallest scales, the beam splitter that separates the laser beams should bounce around. In the time it takes a photon to travel out from the laser, down the two arms and back again, the beam splitter will have moved a tiny bit in a random direction. This movement should be picked up by the interferometers as a small change in light output. Over time this changing output creates a signal that appears to be noise. If the second interferometer detects noise in the exact same pattern, the experimenters will conclude that the cause of the noise is the jitter of space.

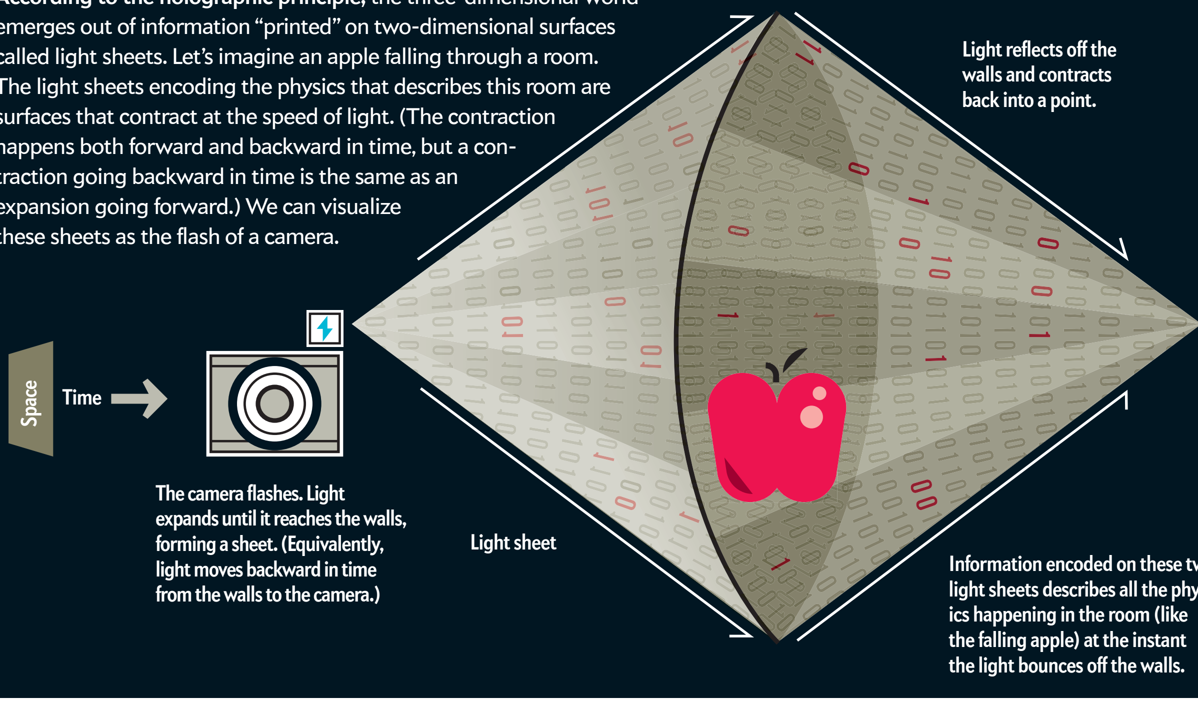


Illustrations by Leandro Castelao

THE HOLOGRAPHIC PRINCIPLE

Information on a Sheet

According to the holographic principle, the three-dimensional world emerges out of information "printed" on two-dimensional surfaces called light sheets. Let's imagine an apple falling through a room. The light sheets encoding the physics that describes this room are surfaces that contract at the speed of light. (The contraction happens both forward and backward in time, but a contraction going backward in time is the same as an expansion going forward.) We can visualize these sheets as the flash of a camera.



A typical experiment at the LHC might include more than 3,000 researchers. At Fermilab, Hogan has assembled a loosely knit team of 20 or so, a figure that includes senior advisers at the Massachusetts Institute of Technology and the University of Michigan who do not participate in day-to-day work at the site. Hogan is primarily a theoretical physicist—largely unfamiliar with the vagaries of vacuum pumps and solid-state lasers—and so he has enlisted as co-leader Aaron Chou, an experimentalist who happened to arrive at Fermilab at about the same time Hogan was putting his proposal forward. In 2011 they were awarded $2 million, which at the LHC would buy you a superconducting magnet and a cup of coffee. The money will fund the entire project. "We don't do any high-tech thing if low-tech will do," Hogan says.

The experiment is so cheap because it is basically an update of the experiment that so famously destroyed the 19th century's established wisdom about the backdrop of existence. By the early 1800s physicists knew that light behaved as a wave. And waves, scientists knew. From a ripple in a pond to sound moving through the air, all waves seemed to share a few essential features. Like sculptures, waves always require a medium—some physical substrate that the waves must travel through. Because light is a wave, the thinking went, it must also require a medium, an invisible substance that permeated the universe. Scientists called this hidden medium the ether.

In 1887 Albert Michelson and Edward Morley designed an experiment that would search for this ether. They set up an interferometer—a device with two arms in the shape of an L that was optimized to measure change. A single source of light would travel the length of both arms, bounce off mirrors at the ends, then recombine where it began. If the length of time it took the light to travel down either arm changed by even a fraction of a microsecond, the recombined light would glow darker. Michelson and Morley set up their interferometer and monitored the light for months as the earth moved around the sun. Depending on which way the earth was traveling, the stationary ether should have altered the time it took for the light to bounce down the perpendicular arms. Measure this change, and you have found the ether.

Of course, the experiment found no such thing, thus beginning the destruction of a cosmology hundreds of years old. Yet like a forest obliterated by fire, clearing the ether made it possible for revolutionary new ideas to flourish. Without an ether, light traveled the same speed no matter how you were moving. Decades later Albert Einstein seized this insight to derive his theories of relativity.

Hogan's interferometer will search for a backdrop that is much like the ether—an invisible (and possibly imaginary) substrate that permeates the universe. By using two Michelson interferometers stacked on top of each other, he intends to probe the smallest scales in the universe, the distance at which both quantum mechanics and relativity break down—the region where information lives as bits.

THE PLANCK SCALE IS NOT JUST SMALL—IT IS THE smallest. if you took a particle and confined it inside a cube less than one Planck length on each side, general relativity says that it would weigh more than a black hole of that same size. But the laws of quantum mechanics say that any black hole smaller than a Planck length must have less than a single quantum of energy, which is impossible. At the Planck length lies paradox.

Yet the Planck length is much more than the space where quantum mechanics and relativity fall apart. In the past few decades an argument over the nature of black holes has revealed a wholly new understanding of the Planck scale. Our best theories may break down there, but in their place something else emerges. The essence of the universe is information, so this line of thinking goes, and the fundamental bits of information that give rise to the universe live on the Planck scale.

As explained by Stanford University physicist Leonard Susskind during a public lecture in 2011, "information" is about distinctions. "It is a very basic principle of physics that distinctions never disappear," he said. "They might get scrambled or all mixed up, but they never go away." Even after this magazine gets dissolved into pulp at the recycling plant, the information on these pages will be reorganized, not eliminated. In theory, the decay can be reversed—the pulp reconstructed into words and photographs—even if, in practice, the task appears impossible.

Physicists have long agreed on this principle except in one special case. What if this magazine were to be thrown into a black hole? Nothing can ever emerge from a black hole, after all. Throw these pages into a black hole, and that black hole will appear almost exactly the same as it did before—just a few grams heavier, perhaps. Even after Stephen Hawking showed in 1975 that black holes can radiate away matter and energy (in the form that we now call Hawking radiation), this radiation seemed to be devoid of structure, a flat bleat at the cosmos. He thus concluded that black holes must destroy information.

SPACE DOES NOT SIT STILL, A SMOOTH BACKDROP TO THE COSMOS. INSTEAD QUANTUM FLUCTUATIONS MAKE SPACE BRISTLE AND VIBRATE, SHIFTING THE WORLD ALONG WITH IT.

Nonsense, argued a number of Hawking's colleagues, among them Susskind and Gerard 't Hooft, a theoretical physicist at Utrecht University in the Netherlands who would go on to win the Nobel Prize in 1999. "The whole structure of everything we know would disintegrate if you opened the door even a tiny bit for the notion of information to be lost," Susskind says.

Hawking was not easily convinced, however, and so over the following two decades physicists developed a new theory that could account for the discrepancy. This is the holographic principle, and it holds that when an object falls into a black hole, the stuff inside may be lost, but the object's information is somehow imprinted onto a surface around the black hole. With the right tools, you could theoretically reconstruct this magazine from a black hole just as you could from the pulp at the recycling plant. The black hole's event horizon—the point of no return—serves double duty as a ledger. Information is not lost.

The principle is more than just an accounting trick. It implies that whereas the world we see around us appears to take place in three dimensions, all the information about it is stored on surfaces that have just two dimensions [see "Information in the Holographic Universe," by Jacob D. Bekenstein; Scientific American, August 2003]. What is more, there is a limit to how much information can be stored on a given surface area. If you divide a surface up like a checkerboard, each square two Planck lengths on a side, the information content will always be less than the number of squares.

In a series of papers in 1999 and 2000 Raphael Bousso, now at the University of California, Berkeley, showed how to extend this holographic principle beyond the simple surfaces around black holes. He imagined an object surrounded by flashbulbs popping off in the dark. Light that traveled inward defined a surface—a bubble collapsing at the speed of light. It is on this two-dimensional surface—the so-called light sheet—that all the information about you (or a flu virus or a supernova) is stored [*see box on opposite page*].

This light sheet, according to the holographic principle, does a lot of work. It contains information about the position of every particle inside the sheet, every electron and quark and neutrino, and every force that acts on them. Yet it would be wrong to think about the light sheet as a piece of film, passively recording the real stuff that happens out in the world. Instead the light sheet comes first. It projects the information contained on its surface out into the world, creating all that we see. In some interpretations, the light sheet does not just generate all the forces and particles—it gives rise to the fabric of spacetime itself. "I believe that spacetime is what we call emergent," says Herman Verlinde, a physicist at Princeton University and a former student of 't Hooft. "It will come out of a bunch of 0's and 1's."

One problem: although physicists mostly agree that the holographic principle is true—that information on nearby surfaces contains all the information about the world—they know not how the information is encoded, or how nature processes the 1's and 0's, or how the result of that processing gives rise to the world. They suspect the universe works like a computer—that information conjures up what we perceive to be physical reality—but right now that computer is a big black box.

Ultimately the reason why physicists are so excited about the holographic principle, the reason they spent decades developing it—other than convincing Hawking that he was mistaken, of course—is because it articulates a deep connection among information, matter and gravity. In the end, the holographic principle could reveal how to reconcile the two tremendously successful yet mutually incompatible pillars of 20th-century physics: quantum mechanics and general relativity. "The holographic principle is a signpost to quantum gravity," Bousso says, an observation that points the way toward a theory that will supersede our current understanding of the world. "We might need more signposts."

INTO ALL THIS CONFUSION COMES HOGAN, WITH NO grand theory of everything, armed with his simple Holometer. But Hogan does not need a grand theory. He does not have to solve all these difficult problems. All he has to do is figure out one fundamental fact: Is the universe a bitlike world, or isn't it? If he can do that, he will indeed have produced a signpost—a giant arrow pointing in the direction of a digital universe, and physicists would know which way to go.

According to Hogan, in a bitlike world, space is itself quantum—it emerges from the discrete, quantized bits at the Planck scale. And if it is quantum, it must suffer from the inherent uncertainties of quantum mechanics. It does not sit still, a smooth backdrop to the cosmos. Instead quantum fluctuations make space bristle and vibrate, shifting the world around with it. “Instead of the universe being this classical, transparent, crystalline-type ether,” says Nicholas B. Suntzeff, an astronomer at Texas A&M University, “at a very, very small scale, there are these little foamlike fluctuations. It changes the texture of the universe tremendously.”

The trick is getting down to the level of this spacetime foam and measuring it. And here we run into the problem of the Planck length. Hogan’s Holometer is an attempt to flank a full-scale assault on the Planck length—a unit so small that measuring it with a conventional experiment (such as a particle accelerator) would involve building a machine the approximate size of the Milky Way.

Back when Michelson and Morley were investigating the (nonexistent) ether, their interferometer measured a tiny change—the change in the speed of light as the earth moved around the sun—by comparing two light beams that had traveled a reasonably long way. In effect, that distance multiplied the signal. So it is with Hogan’s Holometer. His strategy for getting down to the Plank length is to measure the accumulated errors that accrue when dealing with any jittery quantum system.

“If I look at my TV set or my computer monitor, everything looks nice and smooth,” Chou says. “But if you look at it close-up, you can see the pixels.” As it would be with spacetime. At the level we humans are comfortable with—the scale of people and buildings and microscopes—space appears to be this smooth, continuous thing. We never see a car move down the street by instantaneously leaping from one place to the next as if lit by God’s own strobe light.

Yet in Hogan’s holographic world, this is exactly what happens. Space is itself discrete—or, in the parlance of our times, “quantized” [see “Atoms of Space and Time,” by Lee Smolin; Scientific American, January 2004]. It emerges out of some deeper system, some fundamentally quantum system that we do not yet understand. “It’s a slight cheat because I don’t have a theory,” Hogan says. “But it’s only a first step. I can say to these gravitational theorists, ‘You guys figure out how it works.’ ”

HOGAN’S HOLOMETER IS SET UP MUCH LIKE MICHELSON and Morley’s, if Michelson and Morley had access to microelectronics and two-watt lasers. A laser hits a beam splitter that separates the light into two. These beams travel down the two 40-meter-long arms of an L-shaped interferometer, bounce off mirrors at each end, then return to the beam splitter and recombine. Yet instead of measuring the motion of the earth through the ether, Hogan is measuring any change in the length of the paths as a result of the beam splitter being jostled around on the fabric of space. If at the Planck scale, spacetime thrashes around like a roiling sea, the beam splitter is the dinghy pitching through the froth. In the time it takes the laser beams to travel out and back through the Holometer, the beam splitter will have jiggled just enough Planck lengths for its motion to be detected [*see box on page 107*].

Of course, you might imagine a lot of reasons why a beam splitter might move a few Planck lengths here and there—the rumbling of a car engine outside the building, for instance, or a stiff Illinois wind shaking the foundations.

Such concerns have bedeviled the scientists behind another interferometry project, the twin Laser Interferometer Gravitational-Wave Observatory (LIGO) detectors outside of Livingston, La., and Hanford, Wash. These massive experiments were built to observe gravitational waves—the ripples in spacetime that follow cosmic cataclysms such as neutron star collisions. Unfortunately for the LIGO scientists, gravitational waves shake the ground at the same frequency as other not so interesting things—passing trucks and falling trees, for instance. As such, the detectors have to be completely isolated against noise and vibration. (A proposed wind farm near the Hanford facility caused much consternation among physicists because the mere vibration of the blades would have swamped the detectors with noise.)

The shaking that Hogan is looking for happens much faster—a vibration that jitters back and forth a million times a second. As such, it is not subject to the same noise concerns—only the possible interference from nearby AM radio stations broadcasting at the same frequency. “Nothing moves at that frequency,” says Stephan Meyer, a University of Chicago physicist and LIGO veteran who is working on the Holometer. “If we discover that it’s moving anyway, that’s one of the things that we’ll take as a sure sign” that the jitter is real.

And in the world of particle physics, sure signs can be hard to come by. “This is old-fashioned in a way,” Hogan says. “It appeals to this old-fashioned style of physics, which is, ‘We’re going to go and find out what nature does, without prejudice.’ ” To illustrate, he likes to tell a parable about the origins of relativity and quantum mechanics. Einstein invented the theory of general relativity by sitting at his desk and working out the mathematics from first principles. There were few experimental quandaries that it solved—indeed, its first real experimental test would not come for years. Quantum mechanics, on the other hand, was imposed on the theorists by the puzzling results of experiments. (“No theorist in his right mind would have invented quantum mechanics unless forced to by data,” Hogan says.) Yet it has become the most successful theory in the history of science.

In the same way, theorists have for many years been building beautiful theories such as string theory, although it remains unclear how or if it can ever be tested. Hogan sees the purpose of his Holometer as a way to create the puzzling data that future theorists will have to explain. “Things have been stuck for a long time,” he says. “How do you unstick things? Sometimes they get unstuck with an experiment.” SA

Michael Moyer is a senior editor at *Scientific American.*

MORE TO EXPLORE

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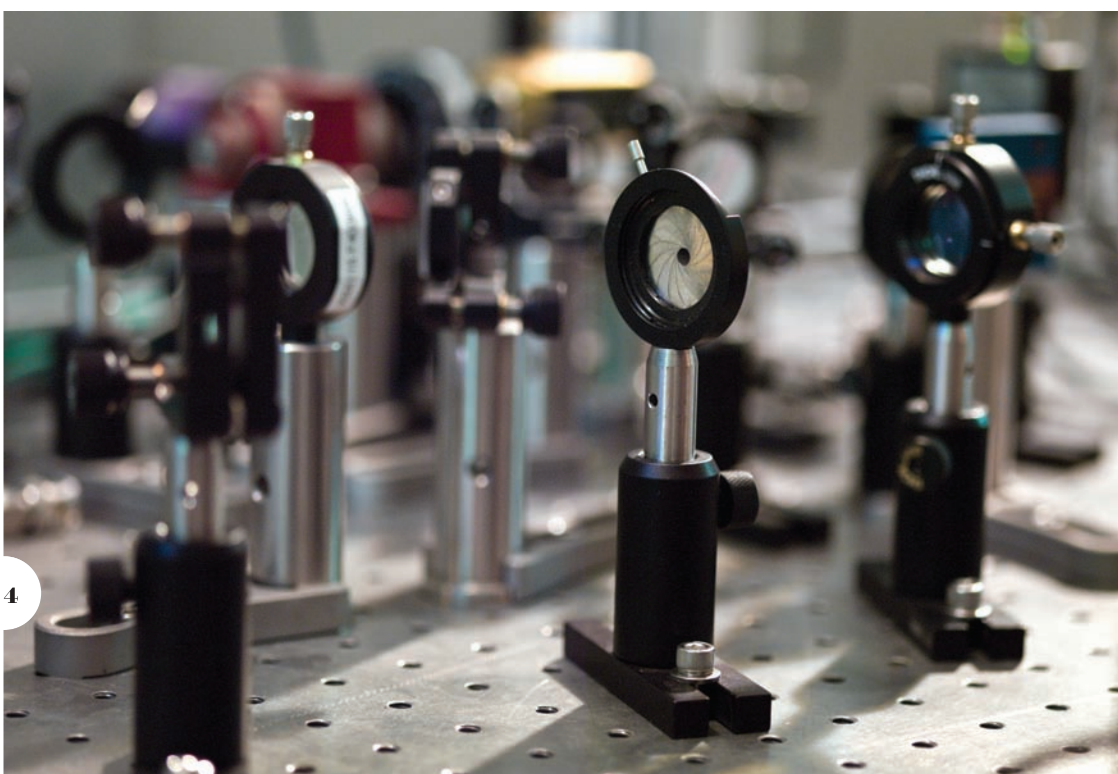

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CRAIG HOGAN (*1*), director of the Fermilab Center for Particle Astrophysics, pauses in his office. Hogan and his team are building the Holometer at a site about a kilometer away. The experiment will send laser beams down 40-meter-long beam tubes (*2*) under vacuum. One set of beam tubes is being housed in a bunker formerly used for particle beams; the other juts out into the countryside, ending at a blue shed that houses a mirror and focusing optics (*3*). Precise optical equipment (*4*) is used to focus and align the beams.

Photographs by Matt Siber