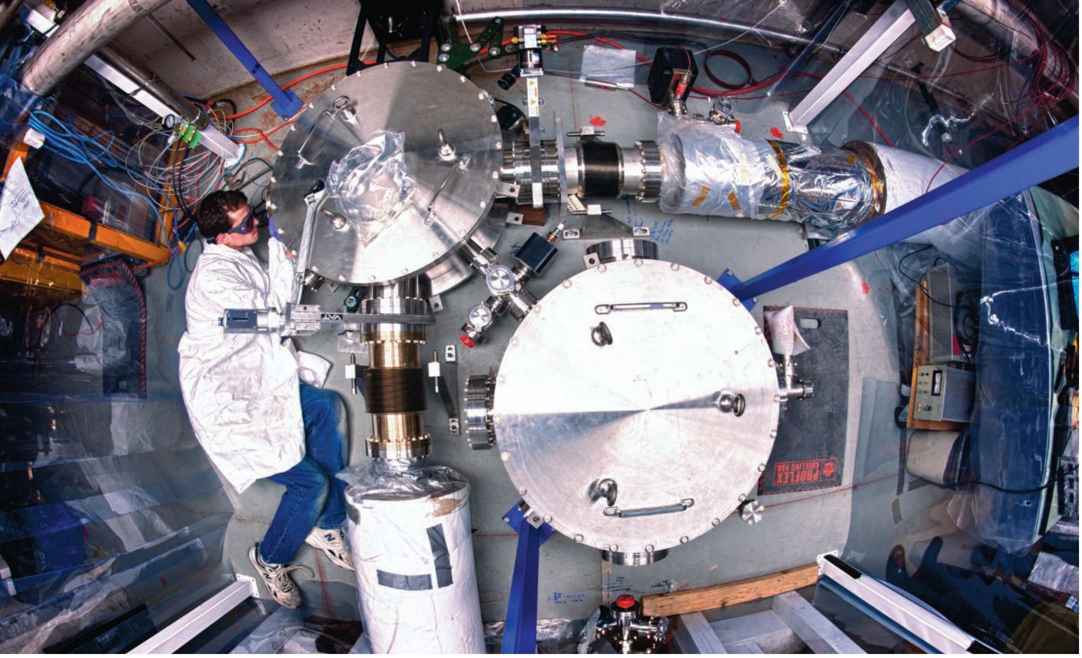

Hands-on. Student Benjamin Brubaker tinkers with the Fermilab holometer.

CREDIT: REIDAR HAHN/FERMILAB

PHYSICS

Sparks Fly Over Shoestring Test Of 'Holographic Principle'

A team of physicists says it can use lasers to see whether the universe stores information like a hologram. But some key theorists think the test won't fly

BATAVIA, ILLINOIS—The experiment looks like a do-it-yourself project, the scientific equivalent of rebuilding a 1983 Corvette in your garage. In a dimly lit, disused tunnel here at Fermi National Accelerator Laboratory (Fermilab), a small team of physicists is constructing an optical instrument that looks like water pipes bolted to the floor. Three scientists huddle within a makeshift tent—really a plastic sheet the size of a tablecloth—to install a high-precision mirror. Nitrogen from a tank flows under the plastic to keep the mirror clean. "It doesn't look very impressive, but it's the equivalent of a class 100 clean room—the best you can buy," says Craig Hogan, a theorist at Fermilab and the University of Chicago in Illinois.

A ratchet clicks as a physicist inside the tent tightens a bolt. Another shouts, "The front one, not the back one! The front one, not the back one!" As implausible as it seems, the homey experiment could revolutionize scientists' conception of the fabric of the universe—if Hogan is right.

Known as the Fermilab holometer, the experiment aims to test one interpretation of the so-called holographic principle. The principle states that the amount of information that can be crammed into a region of space and time, or spacetime, is proportional to the region's surface area. That's odd, as after all, the number of computer hard drives that fit in a room increases with the room's volume, not the area of its walls. If the holographic principle holds, then the universe is a bit like a hologram, a two-dimensional structure that only appears to be three-dimensional. Proving that would be a big step toward formulating a quantum theory of spacetime and gravity—perhaps the single biggest challenge in fundamental physics.

The principle implies a kind of information shortage that, in Hogan's interpretation, makes it impossible to say precisely where an object is. "Think back to kindergarten; you know that something is either here or it's there," Hogan says. "It's so obvious that it's not clear that [position] is a mystery." In fact, Hogan says, position is inherently uncertain, and the holometer aims to prove that point.

All the experiment takes is a couple of million bucks, two lasers, and a few months of work. That makes the holometer an unusual project for Fermilab, a particle physics lab where scientists typically work on huge accelerators and hundred-million-dollar experiments that run for years. "The beauty of it is that we have the people who can come up with this low-risk, high-reward experiment," says Fermilab's Raymond Tomlin. "It's one shot, and if you discover something you go to Stockholm [to collect a Nobel Prize]. And if you don't see anything, you set a limit."

Not everyone cheers the effort, however. In fact, Leonard Susskind, a theorist at Stanford University in Palo Alto, California, and co-inventor of the holographic principle, says the experiment has nothing to do with his brainchild. "The idea that this tests anything of interest is silly," he says, before refusing to elaborate and abruptly hanging up the phone. Others say they worry that the experiment will give quantum-gravity research a bad name.

Black holes and causal diamonds

To understand the holographic principle, it helps to view spacetime the way it's portrayed in Einstein's special theory of relativity. Imagine a particle coasting through space, and draw its "world line" on a graph with time on the vertical axis and position plotted horizontally (see top figure, p. 148). From the particle's viewpoint, it is always right "here," so the line is vertical. Now mark two points or events on the line. From the earlier one, imagine that light rays go out in all directions to form a cone on the graph. Nothing travels faster than light, so the interior of the "light cone" contains all of spacetime that the first event can affect.

Similarly, imagine all the light rays that can converge on the later event. They define another cone that contains all the spacetime that can influence the second event. The cones fence in a three-dimensional, diamond-like region. According to special relativity, all observers will agree about which points are inside or outside the diamond, no matter how they are moving. The holographic principle states that the amount of information that such a "causal diamond" can hold varies with its surface area.

That might seem like a perverse idea, but it follows from physicists' analysis of black holes. A black hole is a region of extremely strong gravity produced when, for example, a star collapses to a point, cramming an enormous mass into an infinitesimally small volume. Within a certain distance of the point, gravity grows so strong that even light cannot escape.

That distance defines a sphere in space called the "event horizon." In the 1970s, theorists deduced that the amount of information contained in a black hole depends on the surface area of its horizon. One bit of information—which can be 0 or 1—can be encoded in each "Planck area," an area smaller than 10^{-69} square meters. Jacob

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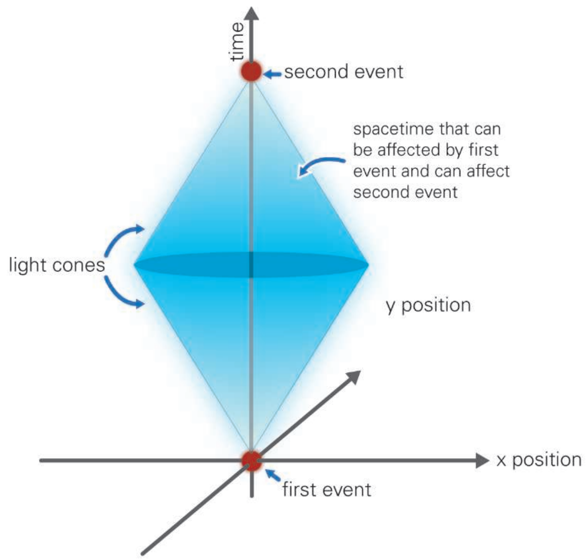
Bekenstein of the Hebrew University in Jerusalem and, independently, Stephen Hawking reached that conclusion when they realized that a black hole must have an entropy—a measure of how disordered it is inside—that grows with the surface area of its event horizon. The more disordered something is, the more information it takes to fully describe it, so the information-area link follows in step.

Known as the Bekenstein bound, that entropy limit would serve as a cornerstone for any theory of quantum gravity, which theorists expect to kick in at length scales shorter than the so-called Planck length—roughly 10^{-35} meters—and time scales shorter than the Planck time, about 10^{-43} seconds. It might have implications far beyond the event horizons of black holes, too. In the 1990s, Susskind and Gerard t'Hooft, a theorist at Utrecht University in the Netherlands, argued that any properly defined region of spacetime will obey the same information-area link, a conjecture that Susskind dubbed the holographic principle.

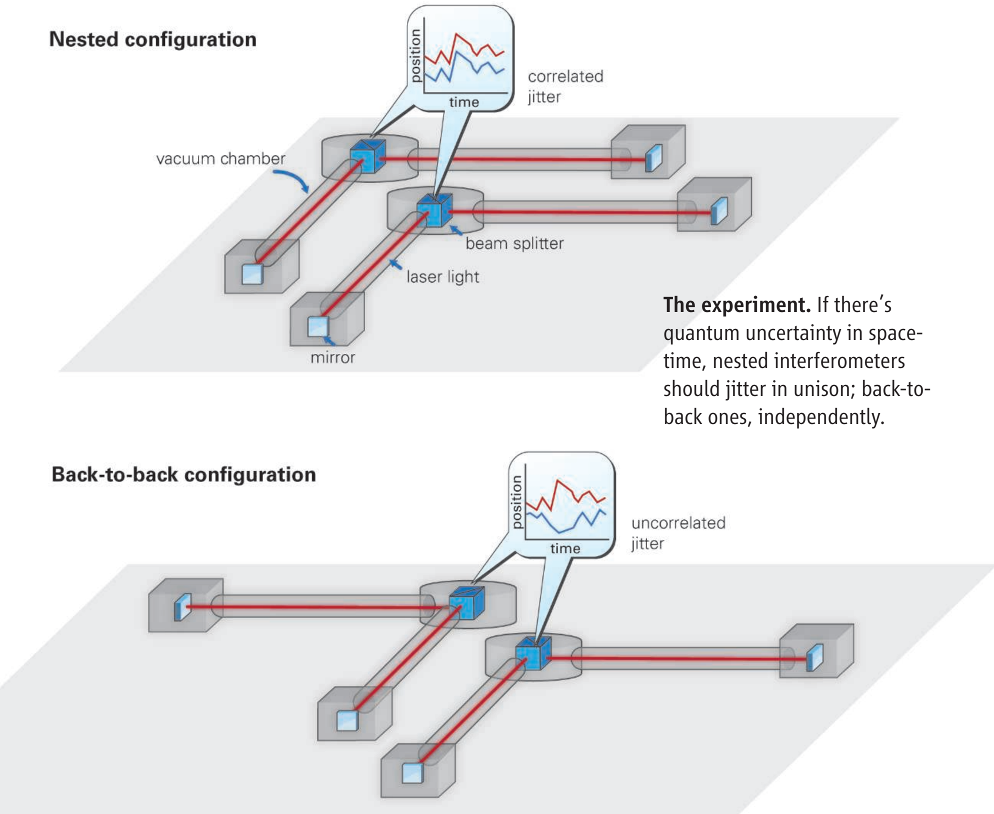
No one has proved that the principle holds. However, no one has come up with a scenario in which it doesn't, says Raphael Bousso of the University of California, Berkeley, who showed how to make the principle jibe with special relativity. For example, suppose you try to exceed the bound by encoding information in individual photons and cramming ever more of them into a region. You'll end up creating a black hole well before you break the limit, Bousso says.

Hogan's interpretation takes matters a long step further. If the area-information link holds, then a region of spacetime can hold less information than it could if the amount of information grew with its volume. The shortage implies that positions in perpendicular directions are no longer independent variables, Hogan argues. The more precisely experimenters measure an object's position in one direction, the less precisely they can know its position in a perpendicular direction. That tradeoff resembles the one imposed by the famous Heisenberg uncertainty principle, which limits an observer's ability to measure both the position and the momentum of a quantum particle.

Specifically, Hogan argues, if researchers know precisely how far away a thing is, then they can't know exactly where it is side to side. That uncertainty should produce a sideways jiggling that grows with the distance to the object, he predicts. That jitter is precisely what physicists hope to observe with the holometer.



The idea. Together, light rays emanating from an earlier event and those converging on a later one form a "causal diamond." The holographic principle says that such a region can hold an amount of information proportional to its surface area.



The experiment. If there's quantum uncertainty in spacetime, nested interferometers should jitter in unison; back-to-back ones, independently.

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Playing with the LEGO LIGO

Physicists at Fermilab plan to measure the jitter using store-bought technology, spare lab space, and a $2.5 million grant from the Department of Energy won for the project by Fermilab's Aaron Chou. That's a mere pittance at a lab that's planning billion-dollar projects. "These huge projects take a long time to design and a longer time to fund, and I worry that by the time one gets built it might not be the most interesting thing in the field," Chou says. "I try to keep an eye out for things that might be done more easily."

To spot the predicted jiggling, physicists are building a pair of L-shaped instruments called interferometers. An interferometer splits an incoming beam of laser light in two using a cube of glass called a "beam splitter." The two beams race down the interferometer's perpendicular arms and reflect off mirrors at the ends. If the lengths of the arms are set just right, then the returning light waves will overlap and interfere so that all the light exits through the same face of the beam splitter that it entered. But if the relative lengths of the arms change, then some light will leak

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out of the perpendicular face, or "dark port," allowing physicists to compare the arms' lengths to a fraction of an atom's width.

An interferometer can also measure the sideways motion of the beam splitter. If the beam splitter moves sideways relative to one of the mirrors, it must necessarily move either toward or away from the mirror in the perpendicular arm, changing that arm's length and letting light leak out of the dark port. So in principle, experimenters can test Hogan's prediction by monitoring the output of a single interferometer for "holographic noise," an unquenchable jitter in the beam splitter's position at frequencies of millions of cycles per second.

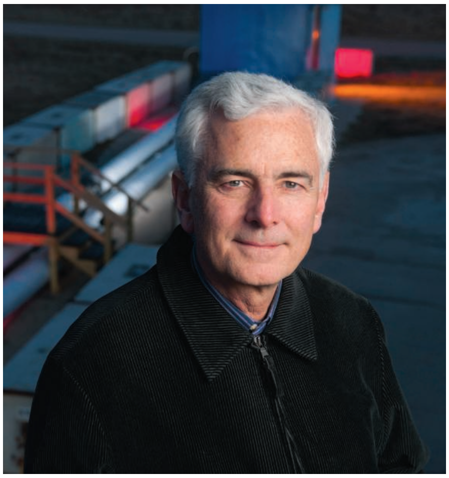
Actually, the team will monitor two interferometers, Chou says. Nested side by side like spoons, the devices will sample the same region of spacetime (see bottom figure, p. 148). That's because in the time that it takes light to bounce through the devices, the causal diamonds of the two beam splitters will overlap. As it is spacetime itself that is fluctuating, the jiggling of the two beam splitters should then be correlated, making it easier to detect a tiny signal—a standard trick from the processing of radio signals. If researchers do see correlated jitter, they can also reconfigure the two devices to sit back to back and sample different regions of spacetime. Any signal from holographic noise should then go away. In the search for a signal, "we'll get a yes or a no," says Stephan Meyer, an experimental cosmologist at the University of Chicago. "There won't be a maybe."

The setup should be incredibly sensitive, Hogan says. If, for any reason, the two beam splitters move in concert by roughly a Planck length per Planck time, then experimenters should be able to detect the motion that accumulates in the fraction of a microsecond it takes light to pass through the apparatus. So the experiment will be able to search for effects on the so-called Planck scale, regardless of their origins. "That's why experimentalists love it," Hogan says.

For a particle physics lab, the holometer experiment is a string-and-sealing-wax affair. Only one of each interferometer's two 40-meter arms will fit in the tunnel. To house the other two arms, researchers have run plastic pipes through the side of the tunnel and the earthen berm that covers it to a wooden shed that resembles an outhouse. The experiment runs out of trailers that may have been new when Ronald Reagan was president.

The holometer team is also borrowing technology. Team members Rainer Weiss and Samuel Waldman of the Massachusetts Institute of Technology in Cambridge also work on the Laser Interferometer Gravitational-Wave Observatory (LIGO), which comprises interferometers in Hanford, Washington, and Livingston, Louisiana, each with 4-kilometer-long arms. They've advised their Fermilab colleagues how to build their instruments with store-bought parts, says Fermilab's Chris Stoughton. "The LEGO LIGO was our catch phrase," he says. "You didn't need to build a big experiment; you just needed to buy the parts and reconfigure them differently."

The holometer project also gives the particle physicists a rare treat: a chance to work in a small team. "This is one of the few experiments where you can get your hands on—and your head around—every part of the experiment," says Robert Lanza, a graduate student at the University of Chicago.



Undaunted. At the least, the experiment will probe the Planck scale, originator Craig Hogan says.

CREDIT: REIDAR HAHN/FERMILAB

Wanna bet?

But will the holometer really test the holographic principle? Aptly enough, uncertainty is high.

Even Hogan acknowledges that his prediction of an observable jittering isn't airtight. He assumes that the uncertainty relationship applies to the position of a macroscopic object. But it could apply just to the subatomic particles within the object, which would produce a much smaller effect. In that case, failure to spot the quivering wouldn't torpedo the basic holographic principle, Hogan says. "If we don't see a signal, nobody is going to abandon these ideas of holography," he says. "On the other hand, if we do see a signal, it will make the whole idea of holography more concrete."

But some experts on the holographic principle think the experiment is completely off-target. "There is no relationship between the argument [Hogan] is making and the holographic principle," Bousso says. "None whatsoever. Zero." The problem lies not in Hogan's interpretation of the uncertainty relationship, but rather in "the first step of his analysis," Bousso contends.

Bousso notes that a premise of special relativity called Lorentz invariance says the rules of physics should be the same for all observers, regardless of how they are moving relative to one another. The holographic principle maintains Lorentz invariance, Bousso says. But Hogan's uncertainty formula does not, he argues: An observer standing in the lab and another zipping past would not agree on how much an interferometer's beam splitter jitters. So Hogan's uncertainty relationship cannot follow from the holographic principle, Bousso argues.

The experiment can do no good in testing the holographic principle, Bousso says, but running it could do plenty of harm. The holometer has garnered an inordinate amount of attention in the blogosphere and in press accounts, he says, raising unrealistic expectations. "They're not going to have a signal and then there is going to be a backlash saying that the holographic principle isn't valid, and we'll look like we're on the defensive," Bousso says. "That's why I'm trying to get the word out [that the experiment won't test the principle] without appearing to make excuses."

Hogan is unruffled. He sticks by his claim that the holographic principle implies an uncertainty in position that may be observable. This uncertainty relationship violates Lorentz invariance, he acknowledges, but the bigger issue is how Lorentz-invariant spacetime itself emerges from deeper physics at the Planck scale. In any case, Hogan says, debating this experiment can only benefit the field of quantum-gravity research, which has remained essentially theoretical. "If we can actually have an argument about an experiment and whether or not we're doing a test of something, I think that's helpful," he says.

At the least, the experiment will probe the Planck scale in some way, Hogan says. "What I would love is for theorists to predict that we won't see anything," he says. "They haven't done that." Then again, they don't have to. Within a year, Hogan and his team will have their data. It would make a thrilling, feel-good story if they scored a huge discovery that served as the basis for a real theory of quantum gravity. In science, however, long shots pay out even less often than they do at the racetrack. **–ADRIAN CHO**