IS SPACE PIXELATED?

The search for signatures of quantum gravity forges ahead

By Whitney Clavin

Sand dunes seen from afar seem smooth and unwrinkled, like silk sheets spread across the desert. But a closer inspection reveals much more. As you approach the dunes, you may notice ripples in the sand. Touch the surface and you would find individual grains. The same is true for digital images: zoom far enough into an apparently perfect portrait and you will discover the distinct pixels that make the picture.

The universe itself may be similarly pixelated. Scientists such as Rana Adhikari, professor of physics at Caltech, think the space we live in may not be perfectly smooth but rather made of incredibly small discrete units. “A spacetime pixel is so small that if you were to enlarge things so that it becomes the size of a grain of sand, then atoms would be as large as galaxies,” he says.

Adhikari and scientists around the world are on the hunt for this pixelation because it is a prediction of quantum gravity, one of the deepest physics mysteries of our time. Quantum gravity refers to a set of theories, including string theory, that seeks to unify the macroscopic world of gravity, governed by general relativity, with the microscopic world of quantum physics. At the core of the mystery is the question of whether gravity, and the spacetime it inhabits, can be “quantized,” or broken down into individual components, a hallmark of the quantum world.

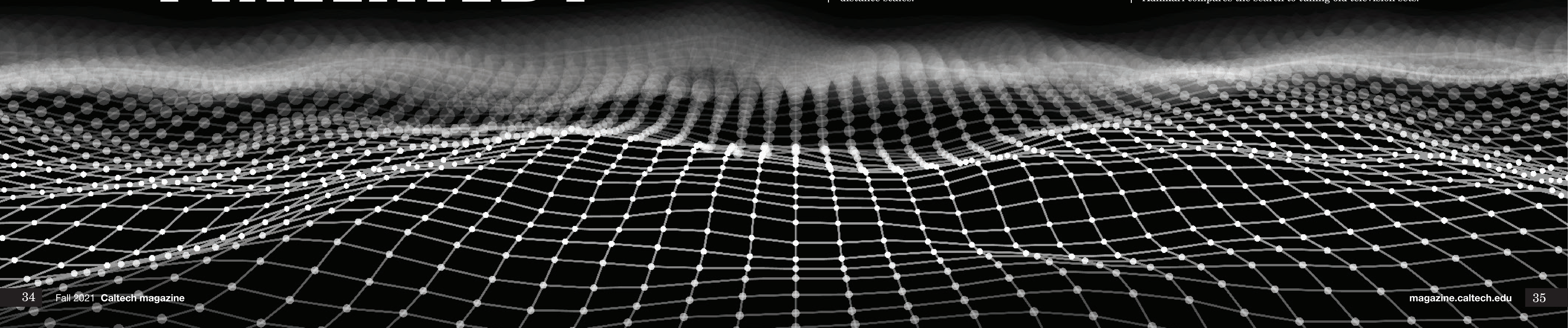
“Sometimes there is a misinterpretation in science communication that implies quantum mechanics and gravity are irreconcilable,” says Cliff Cheung, Caltech professor of theoretical physics. “But we know from experiments that we can do quantum mechanics on this planet, which has gravity, so clearly they are consistent. The problems come up when you ask subtle questions about black holes or try to merge the theories at very short distance scales.”

Because of the incredibly small scales in question, some scientists have deemed finding evidence of quantum gravity in the foreseeable future to be an impossible task. Although researchers have come up with ideas for how they might find clues to its existence—around black holes; in the early universe; or even using LIGO, the National Science Foundation-funded observatories that detect gravitational waves—no one has yet turned up any hints of quantum gravity in nature.

Professor of Theoretical Physics Kathryn Zurek would like to change that. She recently formed a new multi-institutional collaboration, funded by the Heising-Simons Foundation, to think about how to observe signatures of quantum gravity. The project, called Quantum gRavity and Its Observational Signatures (QuRIOS), unites string theorists, who are familiar with the formal tools of quantum gravity but have little practice designing experiments, with particle theorists and model-builders who are experienced with experiments but not working with quantum gravity.

“The idea that you might be able to look for observable features of quantum gravity is very far from the mainstream,” she says. “But we’ll be lost in the desert if we don’t start focusing on ways to link quantum gravity with the natural world that we live in. Having observational signatures to think about tethers us theorists together and helps us make progress on new kinds of questions.”

As part of Zurek’s collaboration, she will work with Adhikari, an experimentalist, to develop a new experiment that uses tabletop instruments. The proposed experiment, called Gravity from Quantum Entanglement of Space-Time (GQuEST), will be able to detect not individual spacetime pixels themselves, but rather connections between the pixels that give rise to observable signatures. Adhikari compares the search to tuning old television sets.



Hirosi Ooguri has developed key mathematical tools for understanding string theory.

"When I was growing up, we could not get NBC, and we would try to tune around to get it. But most of the time, we would see the pixelated snow. Some of that snow we know is coming from the cosmic microwave background, or the birth of the universe, but if you tuned just off the peak of that, you could find snow from solar storms and other signals. That's what we are trying to do: to carefully tune in to the snow, or fluctuations of spacetime. We will be looking to see if the snow fluctuates in ways that align with our models of quantum gravity. Our idea could be bogus, but we have to try."

A new blueprint for the universe

Cracking the problem of quantum gravity would be one of the greatest achievements of physics, on par with the two theories that researchers want to merge. Albert Einstein's general theory of relativity reshaped the view of the universe, showing that space and time can be thought of as one continuous unit, spacetime, which curves in response to matter. Gravity, the theory explains, is nothing more than the curvature of spacetime.

The second theory, quantum mechanics, describes the three other known forces in the universe aside from gravity: electromagnetism, the weak nuclear force, and the strong nuclear force. A defining feature of quantum mechanics is that these forces can be quantized down to discrete packets, or particles. For example, the quantization of the electromagnetic force results in a particle known as the photon, which makes up light. The photon works behind the scenes at microscopic scales to transmit the force of electromagnetism. Though the electromagnetic field appears continuous at the large scales we are used to, it becomes "bumpy" with photons when you zoom in.

The central question of quantum gravity, then, is this: does spacetime also become a frothy sea of particles at the smallest scales, or does it remain smooth like the surface of an unbroken lake? Scientists generally believe that gravity should be bumpy at the smallest scales; the bumps are hypothetical particles called gravitons. But when physicists use mathematical tools to describe how gravity might arise from gravitons at very tiny scales, things break down.

"The math become impossible and produces absurd answers such as infinity where we should get finite numbers as answers. It implies something is amiss," says Hirosi Ooguri, the Fred Kavli Professor of Theoretical Physics and Mathematics and director of the Walter Burke Institute for Theoretical Physics. "It is not well appreciated how hard it is to build a consistent theoretical framework, to unify general relativity and quantum mechanics.

"It would seem to be impossible, but then we have string theory."

Strings at the bottom

Many scientists would agree that string theory is the most complete and probable theory of quantum gravity to date. It describes a universe with 10 dimensions, six of which are squirreled away unseen while the remaining four make up space and time. True to its name, the theory postulates that all matter in the universe is, at the most fundamental level, made of teeny strings. Like a violin, the strings resonate at different frequencies or notes, with each note corresponding to a unique particle such as an electron or photon. One of these notes is thought to correspond to the graviton.

John Schwarz, the Harold Brown Professor of Theoretical Physics, Emeritus, was one of the first people to realize the power of string theory to bridge the gap between the quantum world and gravity. In the 1970s, he and his colleague Joël Scherk struggled to use the mathematical tools of string theory to describe the strong nuclear force. However, they realized the theory's disadvantages could be turned into advantages if they changed course.

"Instead of insisting on constructing a theory of the strong nuclear force, we took this beautiful theory and asked what it was good for," Schwarz said in a 2018 interview. "It turned out it was good for gravity. Neither of us had worked on gravity. It wasn't something we were especially interested in, but we realized that this theory, which was having trouble describing the strong nuclear force, gives rise to gravity. Once we realized this, I knew what I would be doing for the rest of my career."

It turns out that, compared with the other forces, gravity is an oddball. "Gravity is the weakest force we know of," explains Ooguri. "I'm standing here on the fourth floor of the Lauritsen building, and the reason gravity is not pulling me through the floor is that, inside the concrete, there are electrons and nuclei that are supporting me. So, the electric field is winning over the gravitational force."

However, while the strong nuclear force weakens at shorter and shorter distances, gravity becomes stronger.

"The strings help soften this high-energy behavior," Ooguri says. "The energy gets spread out in a string."

Tabletop tests of quantum gravity

The challenge with string theory lies not only in making it consistent with our everyday, low-energy world, but also in testing it. To see what occurs at the minuscule scales where spacetime is theorized to become grainy, experiments would need to probe distances on the order of what is known as the Planck length, or 10^{-35} meters. To reach such extreme scales, scientists would have to build an equally extreme detector. "One way to go is to make something the size of the solar system and look for signatures of quantum gravity that way," says Adhikari. "But that's really expensive and would take hundreds of years!"

Instead, Zurek says, researchers can investigate aspects of quantum gravity using much smaller experiments. "For the lower-energy experiments we are proposing, we don't need the whole machinery of string theory," she says. "Theoretical developments associated with string theory have provided us with some tools and a quantitative grasp on what we expect to be true in quantum gravity."

The experiments proposed by Zurek, Adhikari, and their colleagues focus on effects of quantum gravity that could be observed at more manageable scales of 10^{-18} meters. That is still very small, but potentially doable using very precise laboratory instruments.

These tabletop experiments would be like mini LIGOs: L-shaped interferometers that shoot two laser beams in perpendicular directions. The lasers bounce off mirrors and meet back in their place of origin. In LIGO's case, gravitational waves stretch and squeeze space, which affects the timing of when the lasers meet. The quantum-gravity experiment would look for a different kind of spacetime fluctuation consisting of gravitons that pop in and out of existence in what some call the quantum, or spacetime, foam. (Photons and other quantum particles also pop in and out of existence due to quantum fluctuations.)

Rather than look for the gravitons individually, the researchers seek "long-range correlations" between complicated collections of the hypothetical particles, which result in observable signatures. Zurek explains that these long-range connections are like larger ripples in the sea of spacetime as opposed to the frothy foam where individual particles reside.

Rana Adhikari (left) and Kathryn Zurek (right) have teamed up to develop a new tabletop experiment to look for "long-range correlations" between collections of gravitons.

"We think there are spacetime fluctuations that may perturb the light beams," she says. "We want to design an apparatus where spacetime fluctuations kick a photon out of the beam of the interferometer, and then we would use single-photon detectors to read out that spacetime perturbation."

Emergent spacetime

"Gravity is a hologram," says Monica Jinwoo Kang, a Sherman Fairchild Postdoctoral Fellow in Theoretical Physics at Caltech, when explaining the holographic principle, a key tenet of Zurek's model. This principle, which was realized using string theory in the 1990s, implies that phenomena in three dimensions, such as gravity, can emerge out of a flat two-dimensional surface.

"The holographic principle means that all the information in a volume of something is encoded on the surface," Kang explains.

More specifically, gravity and spacetime are thought to emerge from the entanglement of particles taking place on the 2-D surface. Entanglement occurs when subatomic particles are connected across space; the particles act as a single entity without being in direct contact with each other, somewhat like a flock of starlings. "Modern perspectives on quantum gravity inspired by string theory suggest that spacetime and gravity materialize out of networks of entanglement. In this way of thinking, spacetime itself is defined by how much something is entangled," says Kang.

In Zurek and Adhikari's proposed experiment, the idea would be to probe this 2-D surface, or what they call the "quantum horizon," for graviton fluctuations. Gravity and spacetime, they explain, emerge out of the quantum horizon. "Our experiment would measure the fuzziness of this surface," says Zurek.

That fuzziness would represent the pixelation of spacetime. If the experiment succeeds, it will help redefine our concept of gravity and space at the most fundamental, deepest levels.

"If I drop my coffee mug and it falls, I'd like to think that's gravity," says Adhikari. "But, in the same way that temperature is not 'real' but describes how a bunch of molecules are vibrating, spacetime might not be a real thing. We see flocks of birds and schools of fish undertake coherent motion in groups, but they are really made up of individual animals. We say that the group behavior is emergent. It may be that something that arises out of the pixelation of spacetime has just been given the name gravity because we don't yet understand what the guts of spacetime are."

In Memoriam

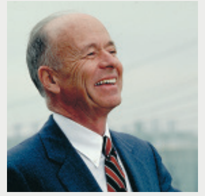
Read more about their lives at **magazine.caltech.edu/post/in-memoriam**

David Grether
1938–2021

David Grether, the Frank Gilloon Professor of Economics, Emeritus, passed away on September 12. He was 82. Grether was trained in econometrics, a field that applies statistical methods to economic data to determine economic relationships. His research into individual decision-making helped develop what was then a new field, experimental economics, which examines economic questions through the use of experiments of auctions, games, and markets.

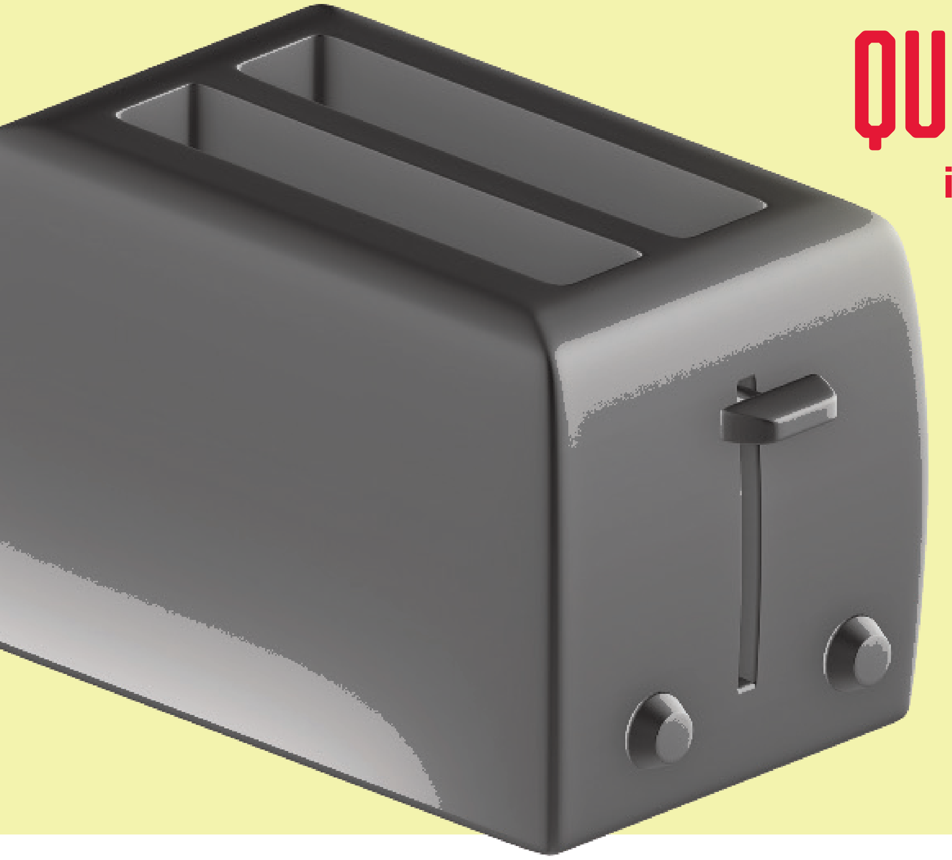
Felix H. Boehm
(MS '51, PhD '54)
1924–2021

Felix H. Boehm, the William L. Valentine Professor of Physics, Emeritus, and a pioneering nuclear physicist, passed away on May 25 at the age of 96. Boehm was among the first to use nuclear physics techniques to do fundamental research on weak interactions and the nature of neutrinos (nearly massless subatomic particles). He initiated the first experiment at a nuclear reactor to look for neutrino oscillations, spontaneous changes of a neutrino's "flavor."



Stephen D. Bechtel, Jr.
1925–2021

Stephen D. Bechtel, Jr., senior director of Bechtel Group Inc. and a life member of the Caltech community, passed away on March 15. He was 95 years old. In 1957, Bechtel founded the S. D. Bechtel, Jr. Foundation, which supports education and environmental programs in California. The construction of Caltech's 211-bed Bechtel Residence, which opened in 2018, was supported by that foundation and the building is named in Bechtel's honor.



QUANTUM PHYSICS in Your Kitchen

Presented by the

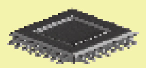
Caltech science exchange

While ubiquitous quantum computers may seem far off, quantum principles are already at work in many technologies available today.

A common kitchen appliance demonstrates one of the phenomena that led to the founding of quantum science:

Inside our toasters, there are metallic elements that glow red when they heat up. Heat any material to the same temperature and the same thing will happen: if you get them hot enough, all materials, metal or not, will glow red, then yellow, then white as they get hotter. This observation provided insight into the field of quantum science. Physicists in the late 1800s and early 1900s proposed that energy emitted from these heated elements was restricted to certain wavelengths, each producing a different visible color. This restricted range is due to the fact that light delivers energy in discrete packets, or "quanta."

Interested in more examples?



Hint: one is probably in your office ceiling, and another is in your phone. Visit **scienceexchange.caltech.edu/quantum** and click on the toaster.

Dive into the quantum realm on the Caltech Science Exchange, and learn why the smallest objects in nature hold the keys to understanding the universe and delivering groundbreaking technology.