ASTRONOMY

Is Our Universe a Hologram? Physicists Debate Famous Idea on Its 25th Anniversary

The Ads/CFT duality conjecture suggests our universe is a hologram, enabling significant discoveries in the 25 years since it was first proposed

By Anil Ananthaswamy on November 30, 2022

Credit: NatalyaBurova/Getty Images

Twenty-five years ago this month, a conjecture shook the world of theoretical physics. It had the aura of revelation. “At first, we had a magical statement … almost out of nowhere,” says Mark Van Raamsdonk, a theoretical physicist at the University of British Columbia, Vancouver. The idea, put forth by Juan Maldacena of the Institute for Advanced Study in Princeton, N.J., hinted at something profound: that our universe could be a hologram. Much like a 3-D hologram emerges from the information encoded on a 2-D surface, our universe’s 4-D spacetime could be a holographic projection of a lower-dimensional reality.

Specifically, Maldacena showed that a five-dimensional theory of a type of imaginary spacetime called anti–de Sitter space (AdS) that included gravity could describe the same system as a lower-dimensional quantum field theory of particles and fields in the absence of gravity, called a conformal field theory (CFT). In other words, he found two different theories that could both describe the same physical system, showing that the theories were, in a sense, equivalent—even though they each included different numbers of dimensions, and one factored in gravity where the other didn't. Maldacena then surmised that this AdS/CFT duality would hold for other pairs of theories, with one having a single extra dimension than the other, possibly even those describing 4-D spacetime like ours.

The conjecture was both intriguing and shocking. How could a theory that included gravity be the same as a theory that had no place for gravity? How could they describe the same universe? But the duality has largely held up. In essence, it argues that the goings-on inside some volume of spacetime that has gravity can be understood by studying the quantum-mechanical behavior of particles and fields at that volume's surface, using a theory with one less dimension, one in which gravity plays no role. "Sometimes some things are easier to understand in one description than the other, and knowing that you're really talking about the same physics is very powerful," says Netta Engelhardt, a theoretical physicist at the Massachusetts Institute of Technology.

In the 25 years since Maldacena mooted the idea, physicists have used this power to address questions about whether or not black holes destroy information, to better understand an early epoch in the our universe's history called inflation, and to arrive at an astonishing conclusion that spacetime may not be fundamental, but something that emerges from quantum entanglement in a lower-dimensional system. Granted, all of these advances involve the theoretically plausible spacetime of anti–de Sitter space, which is not the de Sitter space that describes our universe, but physicists are optimistic that they'll one day arrive at a duality that works for both. If that were to happen, the idea could help develop a theory of quantum gravity, one that would combine Einstein's general relativity with quantum mechanics. It would also imply that our universe is a hologram in truth.

THE ORIGINS OF HOLOGRAPHY

In devising the duality, Maldacena was inspired by work done, in particular, by the late theoretical physicist Joe Polchinski of the University of California, Santa Barbara. Using string theory, in which reality arises from the vibration of impossibly tiny strings, Polchinski developed a theory of objects in string theory called D-branes, which serve as the endpoints for strings that don't close in on themselves.

Maldacena looked at the conformal field theory describing D-branes without gravity on the one hand and an AdS theory with one more dimension of space, but with gravity, on the other. Maldacena noticed similarities between the two theories. In particular, both theories were scale invariant, meaning the physics of the systems the theories described didn't change as the systems got larger or smaller. The lower-dimensional theory also had an additional symmetry, called conformal invariance, where the physical laws don't change for all transformations of spacetime that preserve angles. The AdS theory describing the same objects in the presence of gravity showed similar symmetries. "That these two [theories] have the same symmetries was an important clue," says Maldacena.

Crucially, the quantum field theory describing D-branes was strongly coupled: particles and fields in the theory interacted strongly with each other. The AdS theory was weakly coupled; here particles and fields interacted feebly. Soon, theoreticians found reverse pairings: a lower-dimensional, weakly coupled CFT and its higher-dimensional, strongly coupled AdS counterpart. In all cases, making a calculation is simpler in the weakly coupled system, but because the theories are equivalent, the results can also be used to understand the physics of the strongly coupled theory, without having to do the thornier and often-impossible calculations.

Maldacena described his discovery in a paper submitted to the *International Journal of Theoretical Physics* in November 1997. The idea, however, took some time to sink in. Many physicists began working on trying to make sense of the duality. "There were hundreds, thousands of papers, just checking [the duality], because at first, it [seemed] so ridiculous that some nongravitational quantum theory could actually just be the same thing as a gravitational theory," says Van Raamsdonk. But AdS/CFT held up to scrutiny, and soon began to be used to answer some confounding questions.

ADS/CFT PROVES ITS USEFULNESS

One of the first uses of AdS/CFT had to do with understanding black holes. Theoreticians had long been grappling with a paradox thrown up by these enigmatic cosmic objects. In the 1970s Stephen Hawking showed that black holes emit thermal radiation, in the form of particles, because of quantum mechanical effects near the event horizon. In the absence of infalling matter, this “Hawking” radiation would cause a black hole to eventually evaporate. This idea posed a problem. What happens to the information contained in the matter that formed the black hole? Is the information lost forever? Such a loss would go against the laws of quantum mechanics, which say that information cannot be destroyed.

A key theoretical work that helped tackle this question came in 2006, when Shinsei Ryu and Tadashi Takayanagi used the AdS/CFT duality to establish a connection between two numbers, one in each theory. One pertains to a special type of surface in the volume of spacetime described by AdS. Say there’s a black hole in the AdS theory. It has a surface, called an extremal surface, which is the boundary around the black hole where spacetime makes the transition from weak to strong curvature (this surface may or may not lie inside the black hole’s event horizon). The other number, which pertains to the quantum system being described by the CFT, is called entanglement entropy and is a measure of how much one part of the quantum system is entangled with the rest. The Ryu-Takayanagi result showed that the area of the extremal surface of a black hole in the AdS is related to the entanglement entropy of the quantum system in the CFT.

The Ryu-Takayanagi conjecture promised something alluring. As a black hole evaporates in AdS, the area of its extremal surface changes. This changing area is mimicked by changes to the entanglement entropy calculated in the CFT. And whatever the changes to the entanglement, on the holographic surface described by the CFT, the system evolves according to the rules of quantum mechanics, so information is never lost. This equivalence would imply that black holes in AdS are also not losing information.

There was a hitch though. The Ryu-Takayanagi formula works only in the absence of quantum effects in the AdS theory. “And of course, if a black hole is evaporating, it is evaporating as a result of small quantum corrections,” Engelhardt says. “So we can’t use Ryu-Takayanagi.”

In 2014, Engelhardt and Aron Wall figured out a way to calculate the extremal surface area of a black hole that is subject to the kind of quantum corrections that cause Hawking radiation. Then in 2019, Engelhardt and colleagues, and another researcher independently, showed that the area of these quantum extremal surfaces can be used to calculate the entanglement entropy of the Hawking radiation in the CFT, and that this quantity does indeed follow the dictates of quantum mechanics, consistent with no loss of information (also, they found that the quantum extremal surface lies within the black hole’s event horizon). “This finally gave us a link between something geometric—these quantum extremal surfaces—and something that’s a litmus test of information conservation, which is the behavior of the entropy [when] the information is conserved,” says Engelhardt. “Without AdS/CFT, I doubt that we would have arrived at these conclusions.”

EMERGENT SPACETIME AND QUANTUM ENTANGLEMENT

The connection between entanglement entropy in the CFT and the geometry of spacetime in the AdS led to another important result about the nature of our cosmos, something that Engelhardt and colleagues and Van Raamsdonk and colleagues have worked on. This additional finding is the notion that spacetime on the AdS side emerges from quantum entanglement on the CFT side—not just in black holes but throughout the universe. The idea is best understood by analogy. Think of a very dilute gas of water molecules. Physicists can’t describe the dynamics of this system using the equations of hydrodynamics because the dilute gas does not behave like a liquid. Let’s say that the water molecules condense into a pool of liquid water. Now, the behavior of those very same molecules is subject to the laws of hydrodynamics. “You could ask, originally, where was that hydrodynamics?” says Van Raamsdonk. “It just wasn’t relevant.”

Something similar happens in AdS/CFT. On the CFT side, you can start with quantum subsystems—smaller subsets of the overall system you’re describing—each with fields and particles, without any entanglement. In the equivalent AdS description, you’d have a system with no spacetime. Without spacetime, Einstein’s general relativity is not relevant at this stage, in much the same way that the equations of hydrodynamics don’t apply to a gas of water molecules. But when the entanglement on the CFT side begins increasing, the entanglement entropy of the quantum subsystems starts to correspond to patches of spacetime that emerge in the AdS description. These patches are physically disconnected from each other: going from patch A to patch B isn’t possible without leaving both A and B; however, each individual patch can be described using general relativity. Now, increase the entanglement of the quantum subsystems in the CFT even more, and something intriguing happens in the AdS: the patches of spacetime begin connecting and you eventually end up with a contiguous volume of spacetime. “When you have the right pattern of entanglement, you start to get a spacetime on the other side. It’s almost like the spacetime is a geometrical representation of the entanglement,” says Van Raamsdonk. “Take away all the entanglement and then you just eliminate the spacetime.” Engelhardt agrees. “Entanglement between quantum systems is important for the existence and emergence of spacetime,” she says. The duality suggested that the spacetime of our physical universe might simply be an emergent property of some underlying, entangled part of nature.

Van Raamsdonk credits the AdS/CFT correspondence for making physicists question the very nature of spacetime. If spacetime emerges from the degree and nature of entanglement in a lower-dimensional quantum system, it means that the quantum system is more “real” than the spacetime we live in, in much the same way that a 2-D postcard is more real than the 3-D hologram it creates. “That [space itself and the geometry of space] should have something to do with quantum mechanics is just really shocking,” he says.

Once spacetime emerges in a theory, physicists can use it to study aspects of our universe. For example, our cosmos is thought to have expanded exponentially in the first fractions of a second of its existence, a period known as inflation. In the standard model of cosmology, theorists start with a spacetime in which particles and fields interact weakly and let inflation proceed for about 50–60 "*e*-folds," where each *e*-fold represents more than a doubling of the volume of spacetime (as it increases by a factor of Euler's constant *e,* or approximately 2.718). Such inflation can replicate the properties of the observed universe, such as its flatness and isotropy (the fact that it looks the same in all directions). But there's no particular reason to think that inflation stops at 60 *e*-folds. What if goes on for longer? It turns out that if physicists design models of our universe in which inflation goes on for, say, 70 *e*-folds or more, then the initial state of the universe has to be strongly coupled, one in which fields and particles can interact strongly with each other. So even though a model that allows for this prolonged expansion would be more general, calculations involving strongly -coupled spacetimes are near impossible. "But it's ideally suited to this AdS/CFT approach," says Horatiu Nastase of the São Paulo State University–International, in Brazil.

Nastase has shown how to use the AdS/CFT duality to study a strongly coupled initial state of the universe. It's possible because the CFT side of the duality turns out to be weakly coupled, making calculations tractable. These calculations can then be used to determine the state of the AdS after, say, 70-plus *e*-folds. Nastase has found that a strongly coupled spacetime that inflates for at least 72 *e*-folds can replicate certain observations from our own cosmos, with some fine-tuning of the model's parameters; in particular, the model can match the kind of fluctuations seen in the cosmic microwave background, the fossil radiation from the big bang. "This is ongoing work," says Nastase. "There are a number of issues that are not yet clear."

Physicists hope that such insights will get them to a theory of quantum gravity for our own universe, which would combine general relativity with quantum mechanics. The lack of such a theory is one of the biggest open problems in physics. One fundamental insight from AdS/CFT that underpins all such work is that any theory of quantum gravity will most likely be holographic, in that it'll have a dual description in the form of a theory with one less dimension, without gravity.

The AdS/CFT community is working hard to generalize the correspondence to spacetimes that are more representative of our universe. In AdS, researchers can create a spacetime with cosmic constituents such as black holes, but the spacetime has to be "asymptotically empty," which means that as one goes farther and farther away from a black hole, space becomes empty. "In describing our own universe, we assume that there's stuff everywhere as far as you go," says Van Raamsdonk. "You're never going to run out of galaxies." Also, in AdS, empty space has negative curvature, whereas the empty de Sitter space of our universe is mostly flat.

As influential as AdS/CFT has proved, the duality still uses a spacetime that does not describe our own reality. Maldacena hopes that researchers will find a similar correspondence between de Sitter space—the spacetime we occupy—and a CFT. "I would very much like to have [a] similar statement for de Sitter," says Maldacena. "People keep thinking about it, but no clear contender has emerged so far."

Van Raamsdonk is optimistic that such a candidate will emerge. "If it turns out that our own universe has some underlying quantum picture, some underlying holographic description, if this is really how it works, then I think understanding AdS/CFT will be at the level of understanding quantum mechanics, at the level of understanding general relativity," he says. "[It would be] as big of a leap in our understanding of the universe as anything else that's happened in the history of physics."

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