The elephant and the event horizon

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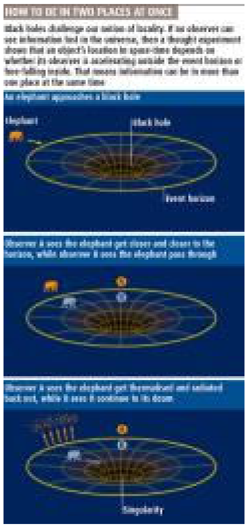
What happens when you throw an elephant into a black hole? It sounds like a bad joke, but it's a question that has been weighing heavily on Leonard Susskind's mind. Susskind, a physicist at Stanford University in California, has been trying to save that elephant for decades. He has finally found a way to do it, but the consequences shake the foundations of what we thought we knew about space and time. If his calculations are correct, the elephant must be in more than one place at the same time.



Enlarge image
How to be in two places at once

In everyday life, of course, locality is a given. You're over there, I'm over here; neither of us is anywhere else. Even in Einstein's theory of relativity, where distances and timescales can change depending on an observer's reference frame, an object's location in space-time is precisely defined. What Susskind is saying, however, is that locality in this classical sense is a myth. Nothing is what, or rather, where it seems.

This is more than just a mind-bending curiosity. It tells us something new about the fundamental workings of the universe. Strange as it may sound, the fate of an elephant in a black hole has deep implications for a "theory of everything" called quantum gravity, which strives to unify quantum mechanics and general relativity, the twin pillars of modern physics. Because of their enormous gravity and other unique properties, black holes have been fertile ground for researchers developing these ideas.

It all began in the mid-1970s, when Stephen Hawking of the University of Cambridge showed theoretically that black holes are not truly black, but emit radiation. In fact they evaporate very slowly, disappearing over many billions of years. This "Hawking radiation" comes from quantum phenomena taking place just outside the event horizon, the gravitational point of no return. But, Hawking asked, if a black hole eventually disappears, what happens to all the stuff inside? It can either leak back into the universe along with the radiation, which would seem to require travelling faster than light to escape the black hole's gravitational death grip, or it can simply blink out of existence.

Trouble is, the laws of physics don't allow either possibility. "We've been forced into a profound paradox that comes from the fact that every conceivable outcome we can imagine from black hole evaporation contradicts some important aspect of physics," says Steve Giddings, a theorist at the University of California, Santa Barbara.

Researchers call this the black hole information paradox. It comes about because losing information about the quantum state of an object falling into a black hole is prohibited, yet any scenario that allows information to escape also seems in violation. Physicists often talk about information rather than matter because information is thought to be more fundamental.

In quantum mechanics, the information that describes the state of a particle can't slip through the cracks of the equations. If it could, it would be a mathematical nightmare. The Schrödinger equation, which describes the evolution of a quantum system in time, would be meaningless because any semblance of continuity from past to future would be shattered and predictions rendered absurd. "All of physics as we know it is conditioned on the fact that information is conserved, even if it's badly scrambled," Susskind says.

For three decades, however, Hawking was convinced that information was destroyed in black hole evaporation. He argued that the radiation was random and could not contain the information that originally fell in. In 1997, he and Kip Thorne, a physicist at the California Institute of Technology in Pasadena, made a bet with John Preskill, also at Caltech, that information loss was real. At stake was an encyclopedia - from which they agreed information could readily be retrieved. All was quiet until July 2004, when Hawking unexpectedly showed up at a conference in Dublin, Ireland, claiming that he had been wrong all along. Black holes do not destroy information after all, he said. He presented Preskill with an encyclopedia of baseball.

What inspired Hawking to change his mind? It was the work of a young theorist named Juan Maldacena of the Institute for Advanced Study in Princeton, New Jersey. Maldacena may not be a household name, but he contributed what some consider to be the most ground-breaking piece of theoretical physics in the last decade. He did it using string theory, the most popular approach to understanding quantum gravity.

In 1997, Maldacena developed a type of string theory in a universe with five large dimensions of space and a contorted space-time geometry. He showed that this theory, which includes gravity, is equivalent to an ordinary quantum field theory, without gravity, living on the four-dimensional boundary of that universe. Everything happening on the boundary is equivalent to everything happening inside: ordinary particles interacting on the surface correspond precisely to strings interacting on the interior.

This is remarkable because the two worlds look so different, yet their information content is identical. The higher-dimensional strings can be thought of as a "holographic" projection of the quantum particles on the surface, similar to the way a laser creates a

3D hologram from the information contained on a 2D surface. Even though Maldacena's universe was very different from ours, the elegance of the theory suggested that our universe might be something of a grand illusion - an enormous cosmic hologram (*New Scientist*, 27 April 2002, p 22).

The holographic idea had been proposed previously by Susskind, one of the inventors of string theory, and by Gerard't Hooft of the University of Utrecht in the Netherlands. Each had used the fact that the entropy of a black hole, a measure of its information content, was proportional to its surface area rather than its volume. But Maldacena showed explicitly how a holographic universe could work and, crucially, why information could not be lost in a black hole.

According to his theory, a black hole, like everything else, has an alter ego living on the boundary of the universe. Black hole evaporation, it turns out, corresponds to quantum particles interacting on this boundary. Since no information loss can occur in a swarm of ordinary quantum particles, there can be no mysterious information loss in a black hole either. "The boundary theory respects the rules of quantum mechanics," says Maldacena. "It keeps track of all the information."

Of course, our universe still looks nothing like the one in Maldacena's theory. The results are so striking, though, that physicists have been willing to accept the idea, at least for now. "The opposition, including Hawking, had to give up," says Susskind. "It was so mathematically precise that for most practical purposes all theoretical physicists came to the conclusion that the holographic principle and the conservation of information would have to be true."

All well and good, but a serious problem remains: if the information isn't lost in a black hole, where is it? Researchers speculate that it is encoded in the black hole radiation (see "Black hole computers"). "The idea is that Hawking radiation is not random but contains subtle information on the matter that fell in," says Maldacena.

Susskind takes it a step further. Since the holographic principle leaves no room for information loss, he argues, no observer should ever see information disappear. That leads to a remarkable thought experiment.

Which brings us back to the elephant. Let's say Alice is watching a black hole from a safe distance, and she sees an elephant foolishly headed straight into gravity's grip. As she continues to watch, she will see it get closer and closer to the event horizon, slowing down because of the time-stretching effects of gravity in general relativity. However, she will never see it cross the horizon. Instead she sees it stop just short, where sadly Dumbo is thermalised by Hawking radiation and reduced to a pile of ashes streaming back out. From Alice's point of view, the elephant's information is contained in those ashes.

Inside or out?

There is a twist to the story. Little did Alice realise that her friend Bob was riding on the elephant's back as it plunged toward the black hole. When Bob crosses the event horizon, though, he doesn't even notice, thanks to relativity. The horizon is not a brick wall in space. It is simply the point beyond which an observer outside the black hole can't see light escaping. To Bob, who is in free fall, it looks like any other place in the universe; even the pull of gravity won't be noticeable for perhaps millions of years. Eventually as he nears the singularity, where the curvature of space-time runs amok, gravity will overpower Bob, and he and his elephant will be torn apart. Until then, he too sees information conserved.

Neither story is pretty, but which one is right? According to Alice, the elephant never crossed the horizon; she watched it approach the black hole and merge with the Hawking radiation. According to Bob, the elephant went through and floated along happily for eons until it turned into spaghetti. The laws of physics demand that both stories be true, yet they contradict one another. So where is the elephant, inside or out?

The answer Susskind has come up with is - you guessed it - both. The elephant is both inside and outside the black hole; the answer depends on who you ask. "What we've discovered is that you cannot speak of what is behind the horizon and what is in front of the horizon," Susskind says. "Quantum mechanics always involves replacing 'and' with 'or'. Light is waves or light is particles, depending on the experiment you do. An electron has a position or it has a momentum, depending on what you measure. The same is happening with black holes. Either we describe the stuff that fell into the horizon in terms of things behind the horizon, or we describe it in terms of the Hawking radiation that comes out."

Wait a minute, you might think. Maybe there are two copies of the information. Maybe when the elephant hits the horizon, a copy is made, and one version comes out as radiation while the other travels into the black hole. However, a fundamental law called the no-cloning theorem precludes that possibility. If you could duplicate information, you could circumvent the uncertainty principle, something nature forbids. As Susskind puts it, "There cannot be a quantum Xerox machine." So the same elephant must be in two places at once: alive inside the horizon and dead in a heap of radiating ashes outside.

The implications are unsettling, to say the least. Sure, quantum mechanics tells us that an object's location can't always be pinpointed. But that applies to things like electrons, not elephants, and it usually spans tiny distances, not light years. It is the large scale that makes this so surprising, Susskind says. In principle, if the black hole is big enough, the two versions of the same elephant could be separated by billions of light years. "People always thought quantum ambiguity was a small-scale phenomenon," he adds. "We're learning that the more quantum gravity becomes important, the more huge-scale ambiguity comes into play."

All this amounts to the fact that an object's location in space-time is no longer indisputable. Susskind calls this "a new form of relativity". Einstein took factors that were thought to be invariable - an object's length and the passage of time - and showed that they were relative to the motion of an observer. The location of an object in space or in time could only be defined with respect to an observer, but its location in space-time was certain. Now that notion has been shattered, says Susskind, and an object's location in space-time depends on an observer's state of motion with respect to a horizon.

What's more, this new type of "non-locality" is not just for black holes. It occurs anywhere a boundary separates regions of the universe that can't communicate with each other. Such horizons are more common than you might think. Anything that accelerates - the Earth, the solar system, the Milky Way - creates a horizon. Even if you're out running, there are regions of space-time from which light would never reach you if you kept speeding up. Those inaccessible regions are beyond your horizon.

As researchers forge ahead in their quest to unify quantum mechanics and gravity, non-locality may help point the way. For instance, quantum gravity should obey the holographic principle. That means there might be redundant information and fewer important dimensions of space-time in the theory. "This has to be part of the understanding of quantum gravity," Giddings says. "It's likely that this black hole information paradox will lead to a revolution at least as profound as the advent of quantum mechanics."

That's not all. The fact that space-time itself is accelerating - that is, the expansion of the universe is speeding up - also creates a horizon. Just as we could learn that an elephant lurked inside a black hole by decoding the Hawking radiation, perhaps we might learn what's beyond our cosmic horizon by decoding its emissions. How? According to Susskind, the cosmic microwave background that surrounds us might be even more important than we think. Cosmologists study this radiation because its variations tell us about the infant moments of time, but Susskind speculates that it could be a kind of Hawking radiation coming from our universe's edge. If that's the case, it might tell us something about the elephants on the other side of the universe.

Black hole computers

Hawking radiation owes its existence to the weirdness of the quantum world, in which pairs of virtual particles pop up out of empty space, annihilate each other and disappear. Around a black hole, virtual particles and anti-particles can be separated by the event horizon. Unable to annihilate, they become real. The properties of each pair are linked, or entangled. What happens to one affects the other, even if one is inside the black hole.

Seth Lloyd of the Massachusetts Institute of Technology believes that this phenomenon can be used to get information out of a black hole. His model, first suggested by Gary Horowitz of the University of California, Santa Barbara, and Juan Maldacena of the Institute for Advanced Study in Princeton, New Jersey, shows that when an in-falling Hawking particle interacts with matter inside the black hole, it sends information about the matter to its partner outside the black hole. If this scheme works, black holes could conceivably be used as quantum computers.

According to Leonard Susskind of Stanford University, however, it makes no sense to talk about the location of information independent of an observer. To an outside observer, information never falls into the black hole in the first place. Instead, it is heated and radiated back out before ever crossing the horizon. The quantum computer model, he says, relies on the old notion of locality. "The location of a bit becomes ambiguous and observer-dependent when gravity becomes important," he says. So the idea of a black hole computer remains controversial.