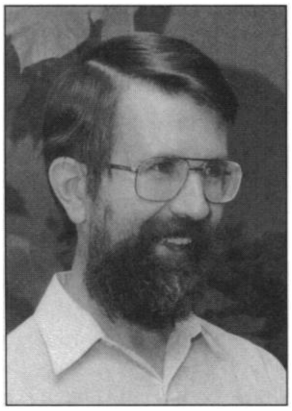
# Plugging a Cosmic Information Leak

**Physicists debate an unnerving proposition: Can black holes deplete the universe of information by sucking it in, then evaporating without a trace?**

The future and the past are both written in the present, or so says contemporary physics. Within the limits set by quantum mechanics, an omniscient super-physicist who cared to measure the velocity, momentum, and every other property of every particle in the universe could predict the color of tomorrow's sunset, find out who killed JFK and how the dinosaurs died, and foresee how and when the world will end. All the information needed to build the universe at any moment in its history has always existed and will always exist, however mixed up it becomes. Trouble comes, however, when you reach the surface of a black hole. There, it appears to physicists, information escapes the universe, determinism gives way to total unpredictability, and the future is cast adrift from the past.



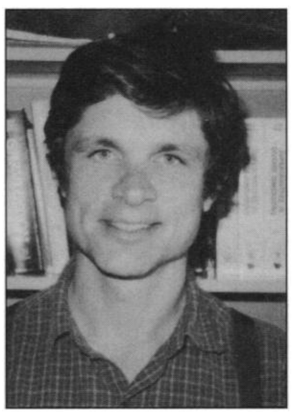
**A narrow escape?** Donald Page speculates that information drawn into a black hole might slip back out.

For physicists, the possibility that information can be lost from the universe is more than strange, it's deeply shocking. It violates everything they've ever been taught about the physical world, going back to Newton, says Princeton University physicist Frank Wilczek. But that possibility has loomed ever since 1976, when Stephen Hawking proposed that black holes can evaporate. Until then, physicists had regarded black holes as unruly but manageable: Though they forever trap matter and the information tied up in it, this information was thought to exist in a kind of cosmic lockbox. Hawking's argument breaks the lock. When black holes evaporate, he argues, they disappear in a haze of particles and radiation that carries no trace of anything that went in. The trapped information vanishes. If he's right, says California Institute of Technology physicist John Preskill, "we'll have to recast fundamental physics."

Not surprisingly, physicists' initial reaction was to look for some way for information to escape this fate. But they've had little success, and, for a time, the topic languished. During the past year, though, there's been a blossoming of interest and new ideas, says Wilczek. Physicists attribute some of the resurgence to a 1992 *Physical Review D* paper by University of California, Santa Barbara, physicist Andrew Strominger and his colleagues Curt Callan, Steve Giddings, and Jeff Harvey, which Strominger says offered simplified approaches to the problem. A flurry of thought and debate followed, leading some physicists to concede that Hawking may be right, while others look for new ways to salvage something from evaporating black holes. Either way, the problem opens the door to some exhilarating physics, say participants. "This may lead us to a fundamentally new insight into the nature of the universe," says Strominger.

At first glance, it's hard to understand why anyone should get wound up about losing information in a world where computer memories crash, stars explode to dust, and people die. But it only appears that the universe loses information, say the physicists. Take, for example, a message written in the snow, says Harvard University theorist Sidney Coleman. When it melts, you might think the information is lost, he says, but in fact the message still exists, somewhere in the pattern of water molecules. "If I could measure the position and velocity of every particle, I could integrate backwards and re-create the message."

Or imagine throwing an encyclopedia into the sun, says Strominger. The words get burned to a crisp, it's true, but in principle, by measuring every photon of radiation coming out, you could reconstruct the encyclopedia. Of course, it's ridiculously difficult to do such a thing, adds Stanford University's Leonard Susskind. "It's not a feasible thing—it's only possible in principle."



**Finding a residue.** A black hole might evaporate into a tiny, information-rich particle, says Andrew Strominger.

### Into the black

Throw the encyclopedia into a black hole, though, and its words and pictures are gone for good. That didn't bother physicists at first, because they thought the information was there, just cut off from outside observers. But it became a problem when Hawking showed that black holes aren't forever—they "evaporate" around the edges. Since nothing can escape a black hole, it's a very roundabout kind of evaporation, which takes place when the black holes absorb particles of negative mass. These particles are a bizarre consequence of quantum mechanics, which implies that empty space bubbles with pairs of "virtual" particles and antiparticles, popping in and out of existence. When this happens near a black hole, said Hawking, one particle, born with negative mass, flies into the hole, attracted to the massive hole as negative charges are attracted to positive. The other partner, which has positive mass, flies away. When all the books are balanced, it looks as though the black hole has lost weight.

Given time, the black hole will eventually shrink to the point of disappearing, leaving behind utterly featureless radiation. And there's the rub, as far as the rest of physics is concerned. "If it's true that Hawking radiation is as featureless as we think, then it would represent true loss of information," says Susskind. Throw in a Bible or a comic book, and the radiation from the evaporating hole would be the same.

For the first few years after Hawking dropped his bombshell, physicists pondering it tended to divide into two camps. A few extremists accept that information really is lost forever and therefore the laws of physics that dictate conservation of information are wrong. That remains Hawking's view, says Susskind. Hawking is well aware that, if he's right, the foundations of physics are in danger: Physicist Donald Page of the University of Alberta, who had been working with Hawking, recalls that Hawking called his original paper "Breakdown of Physics in Gravitational Collapse"—referring to black hole formation as gravitational collapse. (The referees, Page says, made Hawking change the title to something less radical: "The Breakdown of Predictability in Gravitational Collapse.")

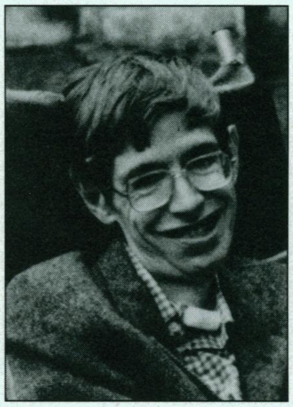
Once Hawking had thrown down this challenge to the conservation of information, some other physicists elaborated on it, dreaming up weird possibilities about the mysterious interiors of black holes that would make the universe even more porous than Hawking had suggested. Page and others have toyed with the idea that information drawn into black holes might slip down "wormholes" that connect our universe to other universes, to be lost to us forever. "A black hole would be like a window in the universe," he says. Not only could information leak out of our own universe through such wormholes, says Page, but information from a black hole in some other universe might pop out of a wormhole into our own. We might face completely unpredictable future events. "A television set could come out," he says.

But Page says he's uncomfortable with the radical implications of total information loss. That's why he is still holding out for the possibility that the information is conserved in spite of black hole evaporation. "There could be ways around it—it's not proven that information is definitely lost." He has speculated that the so-called event horizon of a black hole—the point of no return, at which anything trying to escape a black hole would have to travel faster than light to get out—may not be as formidable a barrier as physicists had thought. Maybe the boundary fluctuates, dipping in far enough to let some information out. In that case, he says, "the horizon is not a watertight container." But like many other physicists debating Hawking's paradox, Page isn't wedded to his ideas. "I'm not even convinced about my own speculation," he says.

**No way out?**

Such efforts to resurrect information from a black hole aren't winning many converts these days, Page concedes. A number of physicists have recently started thinking there may be no escape hatches, including Caltech's Preskill. "I used to believe rather firmly that a black hole shouldn't be different from anything else," he says, meaning that it would somehow give back the information it devours. "Having tried and failed to find the mechanism, I am willing to entertain other possibilities," he says, even Hawking's radical proposition. "I will consider what Hawking said all along—the only solution is to abandon [determinism] and try something else."

Strominger and his colleagues, though, argue that even if there are no escape hatches for information sucked into an evaporating black hole, all of physics doesn't have to go by the board. They have recently embraced the idea that even if the information can't ever come back, it might be preserved in a tiny black-hole residue: a particle-like "remnant," just $10^{-33}$ centimeters across (equal to a fundamental minimum unit of size known as the Planck length) and carrying thousands of times the mass of a proton. This idea, like the others, has taken its share of hits, but Strominger, Rutgers University physicist Thomas Banks, and their colleagues mount a new defense of it in a paper to appear in *Physical Review D*.


MIRIAM BERKELEY

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**Posing the challenge.** Stephen Hawking argues that, having grown by feeding on matter and information, a black hole evaporates in a mist of radiation and eventually vanishes.

Critics of the remnant idea have objected, for example, that each tiny particle would have to have an incredible capacity for storing information. Strominger readily concedes the point: "You can throw the library of Congress into it"—and more. But Strominger and his colleagues propose that the remnants are hiding extra room by curving into higher dimensions. A two-dimensional analogy, says Strominger, would be a flat sheet that dipped into a long throat extending into the third dimension. Each tiny particle thus gains a vast anteroom, giving it an infinite volume to store information, says Strominger.

But that's not enough to save the idea, says Stanford's Susskind. According to quantum mechanics, black hole remnants, like particles, should be forever popping in and out of existence as "virtual particles." And because such remnants could come in an infinite variety of types, depending on the information they sequester, the probability of a virtual remnant popping up at every point in space and time becomes 100%. That would be enough to destroy the universe as we know it.

Strominger says his group can cope with that objection too. Their new approach to the calculations, he says, shows that space and time wouldn't become clotted with remnants, because they don't live by the same rules as ordinary particles. "The key is realizing these are entirely different beasts," he says. "With our methods the rate of production is finite, something manageable—there's no contradiction with experiment" (experiment in this case being the observation that the universe exists).

Not everyone is convinced. Princeton's Wilczek calls the whole remnant idea "far fetched." Wilczek believes that evaporating black holes leave a residue all right—but as he argues in a recent paper in the journal *Nuclear Physics*, it consists of fairly ordinary particles, hardly the thing to store a black hole's lifetime accumulation of information. But that doesn't mean Wilczek is giving in to Hawking and giving up on determinism. He sides with the camp that says information escapes, though he warns that it may take a form too subtle for anyone to notice. The whole paradox might reflect our lack of understanding of what information is. "Information is a fuzzy concept," he says. "It's very important to be careful to specify what you mean." Sometimes the amount of information in a system just depends on how close you look, he says, so you might think you lose it when it's there all the time. Not that he sees a clear resolution of the black hole paradox himself. "We're all confused," he adds.

What's needed, says Susskind, may be a leap of imagination. "We had a paradox like this at the turn of the century," he says, when people believed the universe had one absolute frame of rest and yet experiments showed that light travels at the same speed, regardless of reference frame. "We got the answer from one great man," he says, referring to Einstein, whose theory of relativity altered our concept of time and space. "This time we haven't seen that one great man."

But in the meantime, the paradox is too tempting to ignore, says Preskill; he and his colleagues recognize this as the chink in the armor of modern physics. Its solution, they are convinced, will break down conventional thinking. "I think it's likely there's something fundamental and interesting at the bottom of this," he says. "Whatever it is, it will teach us something very deep."

–**Faye Flam**