BLACK HOLES and the INFORMATION PARADOX

What happens to the information in matter destroyed by a black hole? Searching for that answer, physicists are groping toward a quantum theory of gravity

By Leonard Susskind

SOMEWHERE in outer space, Professor Windbag's time capsule has been sabotaged by his rival, Professor Goulash. The capsule contains a mathematical formula vital to future generations. But Goulash's diabolical scheme to plant a bomb on board has succeeded. Bang! The formula is vaporized into a cloud of electrons, nucleons, photons and an occasional neutrino. Windbag is distraught. He has no record of the formula and cannot remember its derivation.

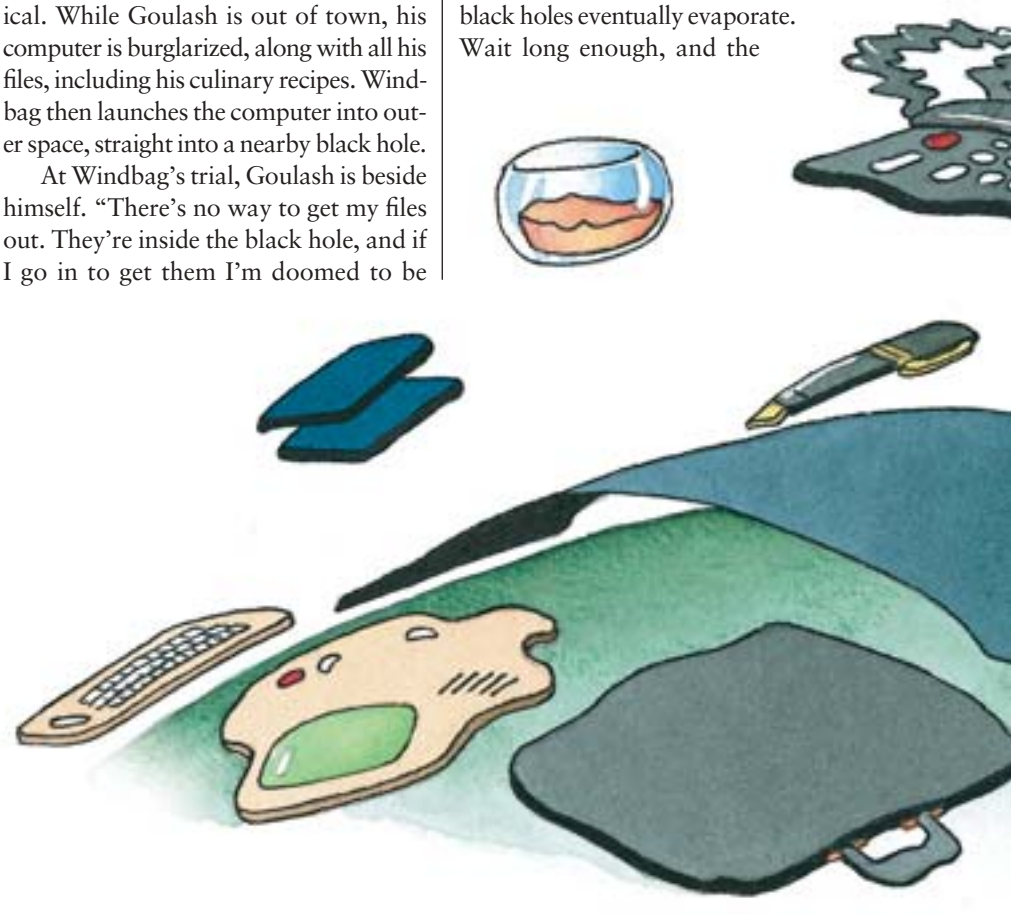
Later, in court, Windbag charges that Goulash has sinned irrevocably: "What that fool has done is irreversible. Off with his tenure!"

"Nonsense," says an unflustered Goulash. "Information can never be destroyed. It's just your laziness, Windbag. All you have to do is go and find each particle in the debris and reverse its motion. The laws of nature are time symmetric, so on reversing everything, your stupid formula will be reassembled. That proves, beyond a shadow of a doubt, that I could never have destroyed your precious information." Goulash wins the case.

Windbag's revenge is equally diabolical. While Goulash is out of town, his computer is burglarized, along with all his files, including his culinary recipes. Windbag then launches the computer into outer space, straight into a nearby black hole.

At Windbag's trial, Goulash is beside himself. "There's no way to get my files out. They're inside the black hole, and if I go in to get them I'm doomed to be crushed. You've truly destroyed information, and you'll pay."

"Objection, Your Honor!" Windbag jumps up. "Everyone knows that black holes eventually evaporate. Wait long enough, and the



BLACK HOLE'S SURFACE looks to Windbag (in the spaceship) like a spherical membrane, called the horizon. Windbag sees Goulash, who is falling into the black hole, being slowed down and flattened at the horizon; according to string theory, Goulash also seems to be spread all over it. Thus, Windbag, who represents the outside observer, sees the information contained in everything that falls into the black hole as stopping at the surface. But Goulash finds himself falling right through the horizon to the center of the black hole, where he becomes crushed.

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black hole will radiate away all its mass and turn into outgoing photons and other particles. True, it may take 10^{70} years, but it's the principle that counts. All Goulash has to do is reverse the paths of the debris, and his computer will come flying back out of the black hole."

"Not so!" cries Goulash. "This is different. My recipe was lost behind the black hole's boundary, its horizon. Once something crosses the horizon, it can never get back out without exceeding the speed of light, and nothing can do that. There is no way the evaporation products, which come from outside the horizon, can contain my recipes even in scrambled form. He's guilty, Your Honor."

Her Honor is confused. "We need some expert witnesses. Professor Hawking, what do you say?"

Stephen W. Hawking of the University of Cambridge comes to the stand. "Goulash is right. In most situations, information is scrambled and in a practical sense is lost. For example, if a new deck of cards is tossed in the air, the original order of the cards vanishes. But in principle, if we know the exact details of how the cards are thrown, the original order can be reconstructed. This is called microreversibility. But in my 1976 paper I showed that the principle of microreversibility, which has always held in classical and quantum physics, is violated by black holes. Because information cannot escape from behind the horizon, black holes are a fundamental new source of irreversibility in nature. Windbag really did destroy information."

Her Honor turns to Windbag: "What do you have to say to that?" Windbag calls on Professor Gerard 't Hooft of Utrecht University in the Netherlands.

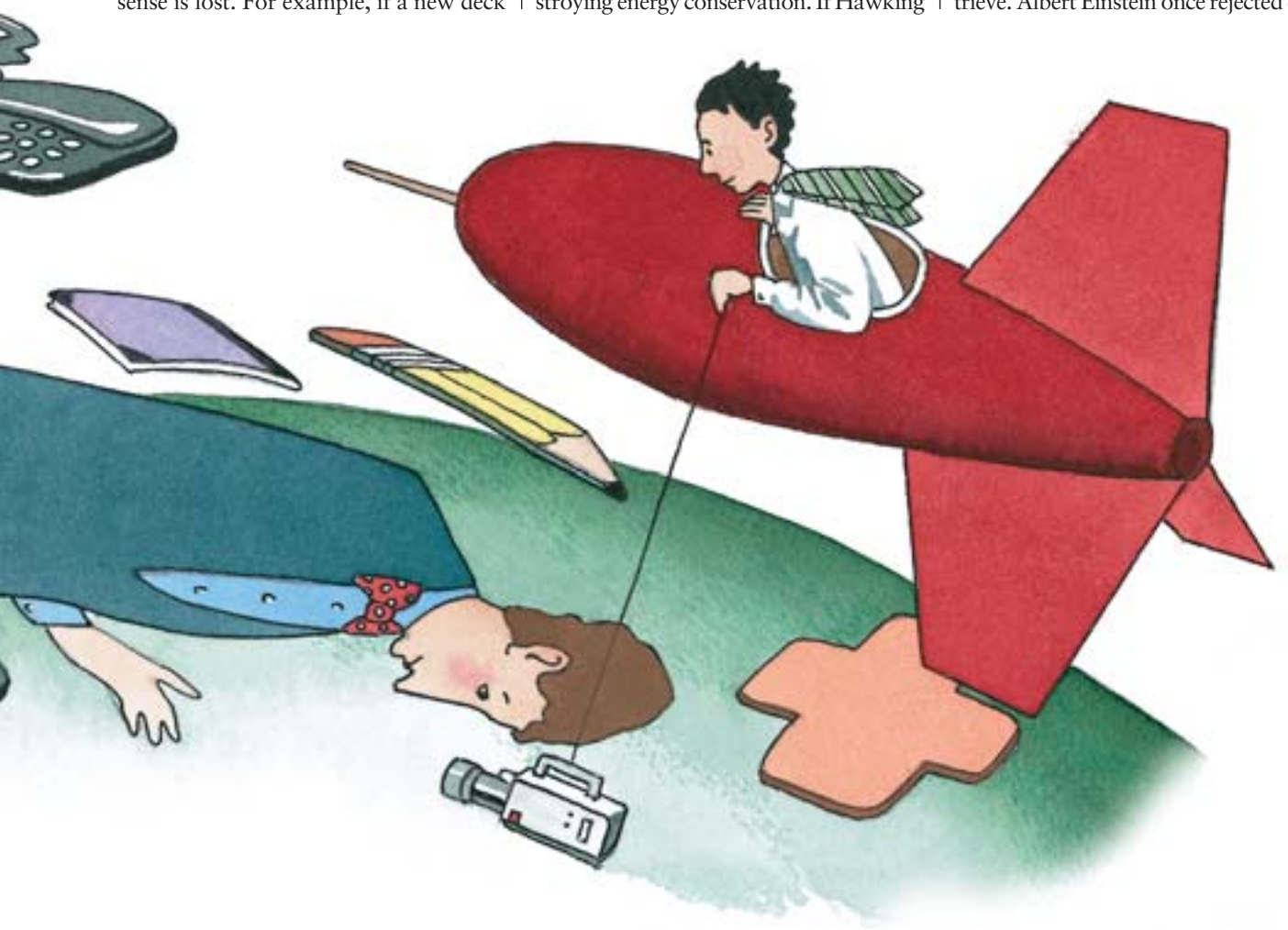
"Hawking is wrong," begins 't Hooft. "I believe black holes must not lead to violation of the usual laws of quantum mechanics. Otherwise the theory would be out of control. You cannot undermine microscopic reversibility without destroying energy conservation. If Hawking were right, the universe would heat up to a temperature of 10^{31} degrees in a tiny fraction of a second. Because this has not happened, there must be some way out."

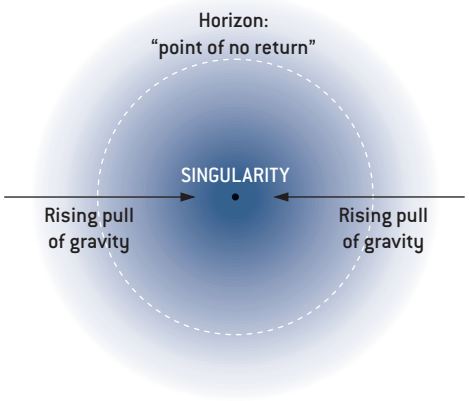
Twenty more famous theoretical physicists are called to the stand. All that becomes clear is that they cannot agree.

The Information Paradox

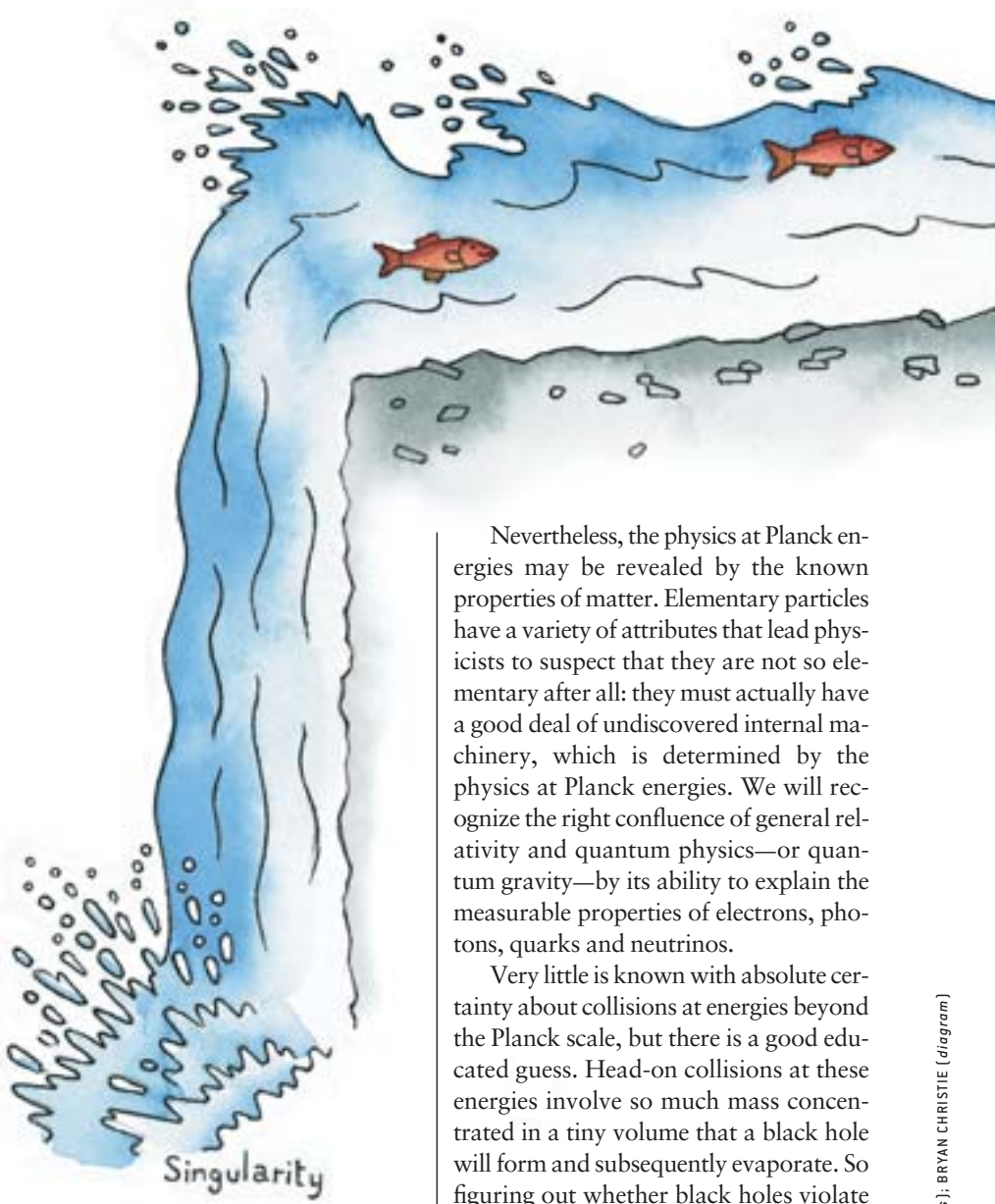
WINDBAG AND GOULASH are, of course, fictitious. Not so Hawking and 't Hooft, nor the controversy of what happens to information that falls into a black hole. Hawking's claim that a black hole consumes information has drawn attention to a potentially serious conflict between quantum mechanics and the general theory of relativity. The problem is known as the information paradox.

When something falls into a black hole, one cannot expect it ever to come flying back out. The information coded in the properties of its constituent atoms is, according to Hawking, impossible to retrieve. Albert Einstein once rejected quan-





INVISIBLE HORIZON is represented in this analogy as a point of no return in a river. To the left of it, water flows faster than a "lightfish" can swim. If a lightfish happens to drift beyond this line, it can never get back upstream; it is doomed to be crushed in the falls. But the fish notices nothing special at the line. Likewise, a light ray or person who is inside the horizon of a black hole can never get out; the object inevitably falls into the singularity at the center but without noticing anything special about the horizon.



tum mechanics with the protest: "God does not play dice." But Hawking states that "God not only plays dice, He sometimes throws the dice where they cannot be seen"—into a black hole.

The problem, 't Hooft points out, is that if the information is truly lost, quantum mechanics breaks down. Despite its famed indeterminacy, quantum mechanics controls the behavior of particles in a very specific way: it is reversible. When one particle interacts with another, it may be absorbed or reflected or may even break up into other particles. But one can always reconstruct the initial configurations of the particles from the final products.

If this rule is broken by black holes, energy may be created or destroyed, threatening one of the most essential underpinnings of physics. The conservation of energy is ensured by the mathematical structure of quantum mechanics, which also guarantees reversibility; losing one means losing the other. As Thomas Banks, Michael Peskin and I showed in 1980 at Stanford University, information loss in a black hole leads to enormous amounts of energy being generated. For such reasons, 't Hooft and I believe the information that falls into a black hole must somehow become available to the outside world.

Some physicists feel the question of what happens in a black hole is academic or even theological. But at stake are the future rules of physics. Processes inside a black hole are merely extreme examples of interactions between elementary particles. At the energies that particles can acquire in today's largest accelerators (about 10^{12} electron volts), the gravitational attraction between them is negligible. But if the particles have a "Planck energy" of about 10^{28} electron volts, so much energy—and therefore mass—becomes concentrated in a tiny volume that gravitational forces outweigh all others. The resulting collisions involve quantum mechanics and the general theory of relativity in equal measure.

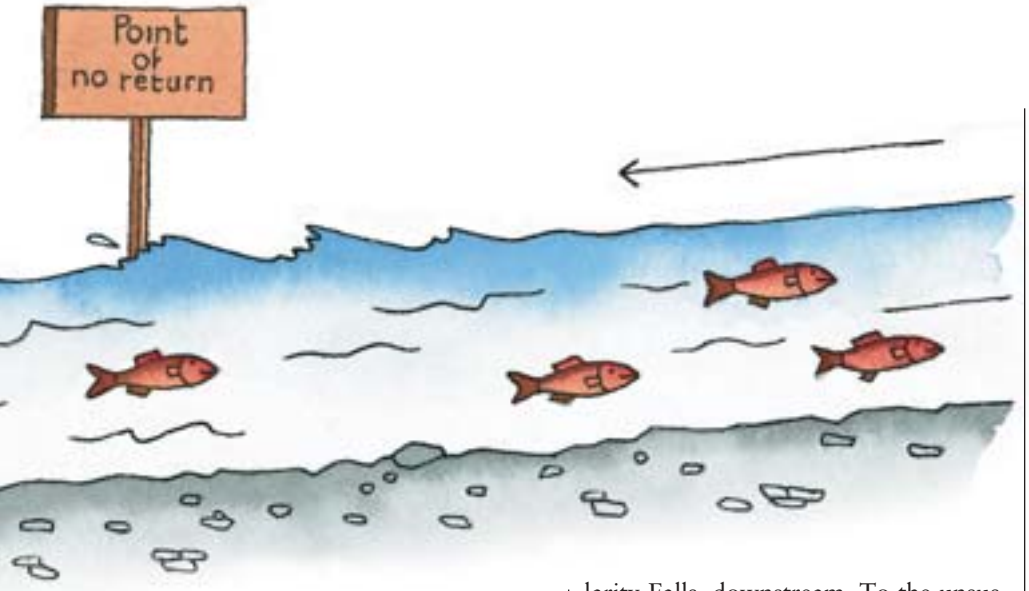
It is to Planckian accelerators that we would nominally look for guidance in building future theories of physics. Alas, Shmuel Nussinov of Tel Aviv University concludes that such an accelerator would have to be at least as big as the entire known universe.

Nevertheless, the physics at Planck energies may be revealed by the known properties of matter. Elementary particles have a variety of attributes that lead physicists to suspect that they are not so elementary after all: they must actually have a good deal of undiscovered internal machinery, which is determined by the physics at Planck energies. We will recognize the right confluence of general relativity and quantum physics—or quantum gravity—by its ability to explain the measurable properties of electrons, photons, quarks and neutrinos.

Very little is known with absolute certainty about collisions at energies beyond the Planck scale, but there is a good educated guess. Head-on collisions at these energies involve so much mass concentrated in a tiny volume that a black hole will form and subsequently evaporate. So figuring out whether black holes violate the rules of quantum mechanics or not is essential to unraveling the ultimate structure of particles.

A black hole is born when so much mass or energy gathers in a small volume that gravitational forces overwhelm all others and everything collapses under its own weight. The material squeezes into an unimaginably small region called a singularity, the density inside of which is essentially infinite. Surrounding the singularity is an imaginary surface called the horizon. For a black hole with the mass of a galaxy, the horizon is 10^{11} kilometers

YAN NASCIMBENE [*illustrations on these and preceding pages*]; BRYAN CHRISTIE [*diagram*]



from the center—as far as the outermost reaches of the solar system are from the sun. For a black hole of solar mass, the horizon is roughly a kilometer away; for a black hole with the mass of a small mountain, the horizon is 10^{-13} centimeter away, roughly the size of a proton.

The horizon separates space into two regions that we can think of as the interior and exterior of the black hole. Suppose that Goulash, who is scouting for his computer near the black hole, shoots a particle away from the center. If he is not too close and the particle has a high velocity, then it may overcome the gravitational pull of the black hole and fly away. It will be most likely to escape if it is shot with the maximum velocity—that of light. If, however, Goulash is too close to the singularity, the gravitational force will be so great that even a light ray will be sucked in. The horizon is the place with the (virtual) warning sign: POINT OF NO RETURN. No particle or signal of any kind can cross it from the inside to the outside.

At the Horizon

AN ANALOGY inspired by William G. Unruh of the University of British Columbia, a pioneer in black hole quantum mechanics, helps to explain the relevance of the horizon. Imagine a river that gets swifter downstream. Among the fish that live in it, the fastest swimmers are the "lightfish." But at some point, the river flows at the fish's maximum speed; clearly, any lightfish that drifts behind this point can never get back up. It is doomed to be crushed on the rocks below Singularity Falls, downstream. To the unsuspecting lightfish, though, passing the point of no return is a nonevent. No currents or shock waves warn it of the crossing.

What happens to Goulash, who in a careless moment gets too close to the black hole's horizon? Like the freely drifting fish, he senses nothing special: no great forces, no jerks or flashing lights. His pulse and breathing rate remain normal. To him the horizon is just like any other place.

But Windbag, watching Goulash from a spaceship safely outside the horizon, sees Goulash acting in a bizarre way. Windbag has lowered to the horizon a cable equipped with a camcorder and other probes. As Goulash falls toward the black hole, his speed increases until it approaches that of light. Einstein found that if two persons are moving fast relative to each other, each sees the other's clock slow down; in addition, a clock that is near a massive object will run slowly compared with one in empty space. Windbag sees an oddly lethargic Goulash. As he falls, the latter shakes his fist at Windbag, but Windbag sees Goulash's motions slow to a halt. Although Goulash falls through the horizon, Windbag never quite sees him get there.

In fact, not only does Goulash seem to slow down, but his body looks as if it is being squashed into a thin layer. Einstein also showed that if two persons move fast with respect to each other, each will see the other as being flattened in the direction of motion. More strangely, Windbag should also see all the material that ever fell into the black hole, including the original matter that made it up—and Goulash's computer—similarly flattened and frozen at the horizon. With respect to an outside observer, all of that matter suffers a relativistic time dilation. To Windbag, the black hole consists of an immense junkyard of flattened matter at its horizon. But Goulash sees nothing unusual until much later, when he reaches the singularity, there to be crushed by ferocious forces.

Black hole theorists have discovered over the years that from the outside, the properties of a black hole can be described in terms of a mathematical membrane above the horizon. This layer has many physical qualities, such as electrical conductivity and viscosity. Perhaps the most surprising of its properties was postulated in the early 1970s by Hawking, Unruh and Jacob D. Bekenstein of the Hebrew University of Jerusalem. They found that as a consequence of quantum mechanics, a black hole—in particular, its horizon—behaves as though it contains heat. The horizon is a layer of hot material of some kind.

The temperature of the horizon depends on where it is measured. Suppose one of the probes that Windbag has attached to his cable is a thermometer. Far from the horizon he finds that the temperature is inversely proportional to the black hole's mass. For a black hole of solar mass, this "Hawking temperature" is about 10^{-8} degree—far colder than intergalactic space. As Windbag's thermometer approaches the horizon, however, it registers higher. At a distance of a centimeter, it measures about a thousandth of a degree; at a nuclear diameter, it records 10 billion degrees. The temperature ultimately becomes so high that no imaginable thermometer could measure it.

THE AUTHOR

LEONARD SUSSKIND is one of the early inventors of string theory. He holds a Ph.D. from Cornell University and has been a professor at Stanford University since 1978. He has made many contributions to elementary particle physics, quantum field theory, cosmology and, most recently, the theory of black holes. His current studies in gravitation have led him to suggest that information can be compressed into one lower dimension, a concept he calls the holographic universe.

Hot objects also possess an intrinsic disorder called entropy, which is related to the amount of information a system can hold. Think of a crystal lattice with N sites; each site can house one atom or none at all. Thus, every site holds one "bit" of information, corresponding to whether an atom is there or not; the total lattice has N such bits and can contain N units of information. Because there are two choices for each site and N ways of combining these choices, the total system can be in any one of 2^N states (each of which corresponds to a different pattern of atoms). The entropy (or disorder) is defined as the logarithm of the number of possible states. It is roughly equal to N—the same number that quantifies the capacity of the system for holding information.

Bekenstein found that the entropy of a black hole is proportional to the area of its horizon. The precise formula, derived by Hawking, predicts an entropy of 3.2×10^{64} per square centimeter of horizon area. Whatever physical system carries the bits of information at the horizon must be extremely small and densely distributed: their linear dimensions have to be $1/10^{20}$ the size of a proton's. They must also be quite special for Goulash to miss them completely as he passes through.

The discovery of the thermodynamic properties of black holes led Hawking to a very interesting conclusion. Like other hot bodies, a black hole must radiate energy and particles into the surrounding space. The radiation comes from the horizon and does not violate the rule that nothing can escape from within. But it causes the black hole to lose energy and mass. In time an isolated black hole radiates away all its mass and vanishes.

All of the above, though peculiar, has been known to relativists for some decades. The true controversies arise when, following Hawking, we seek the fate of the information that fell into the black hole during and after its formation. In particular, can it be carried away by the evaporation products—albeit in a very scrambled form—or is it lost forever behind the horizon?

Goulash, who followed his computer into the black hole, would insist that its contents passed behind the horizon, where they were lost to the outside world; this in a nutshell is Hawking's argument. The opposing point of view might be described by Windbag: "I saw the computer fall toward the horizon, but I never saw it fall through. The temperature and radiation grew so intense I lost track of it. I believe the computer was vaporized; later its energy and mass came back out in the form of thermal radiation. The consistency of quantum mechanics requires that this evaporating energy also carried away all the information in the computer." This is the position that 't Hooft and I take.

Black Hole Complementarity

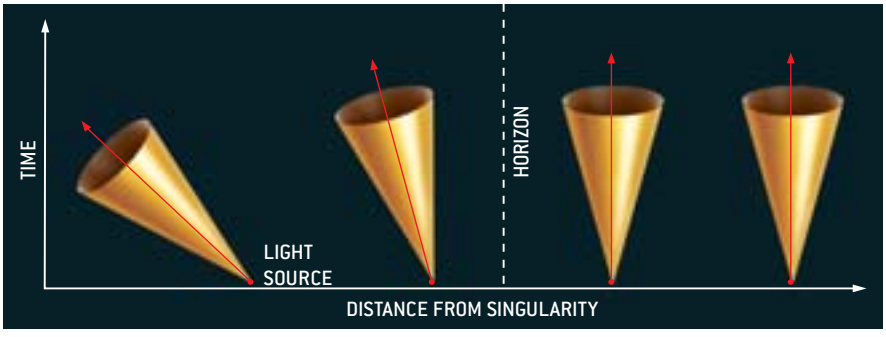
IS IT POSSIBLE that Goulash and Windbag are in a sense both correct? Can it be that Windbag's observations are indeed consistent with the hypothesis that Goulash and his computer are thermalized and radiated back into space before ever reaching the horizon, even though Goulash discovers nothing unusual until long after, when he encounters the singularity? The idea that these are not contradictory but complementary scenarios was first put forward as the principle of black hole complementarity by Lárus Thorlacius, John Uglum and me at Stanford. Very similar ideas are also found in 't Hooft's work. Black hole complementarity is a new principle of relativity. In the special theory of relativity, we find that although different observers disagree about the lengths of time and space intervals, events take place at definite spacetime locations. Black hole complementarity does away with even that.

Suppose that Windbag, whose cable is also equipped with a powerful microscope, watches an atom fall toward the horizon. At first he sees the atom as a nucleus surrounded by a blur of negative charge. But as the atom gets closer to the black hole, its internal motions seem to slow down and the electrons become visible. A little later the electrons freeze, and the protons and neutrons start to show up. Later yet, the quarks making up these particles are revealed. (Goulash, who falls with the atom, sees no changes.)

Quite a few physicists believe elementary particles are made of even smaller constituents. Although there is no definitive theory for this machinery, one candidate stands out: string theory. In this theory, an elementary particle does not resemble a point; rather it is like a tiny rubber band that can vibrate in many modes. The fundamental mode has the lowest frequency; then there are higher harmonics, which can be superimposed on top of one another. There are an infinite number of such modes, each of which corresponds to a different elementary particle.

Here another analogy helps. One cannot see the wings of a hovering hummingbird, because its wings flutter too fast. But in a photograph taken with a fast shutter speed, one can see the wings—so the bird looks bigger. If a hummer falls into the black hole, Windbag will see its wings take form as the bird approaches the horizon and the vibrations appear to slow down; it seems to grow. Now suppose that the wings have feathers that flap even faster. Soon these, too, would come into view, adding further to the apparent size of the bird. Windbag sees the hummer enlarge continuously. But Goulash, who falls with the bird, sees no such strange growth.

Like the hummingbird's wings, the string's oscillations are usually too rapid



LIGHT CONES describe the path of light rays emanating from a point. Outside the horizon the cones point upward—that is, forward in time. But inside, the cones tip so that light falls into the black hole's center.

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to detect. A string is a minute object, $1/10^{20}$ the size of a proton. But as it falls into a black hole, its vibrations slow down and more of them become visible. Mathematical studies done at Stanford by Thorlacius, Amanda W. Peet, Arthur Mezhlumian and me have demonstrated the behavior of a string as its higher modes freeze out. The string spreads and grows, just as if it were being bombarded by particles and radiation in a very hot environment. In a relatively short time the string and all the information it carries are smeared over the entire horizon.

This picture applies to all the material that ever fell into the black hole—because according to string theory, everything is ultimately made of strings. Each elementary string spreads and overlaps all the others until a dense tangle covers the horizon. Each minute segment of string, measuring 10^{-33} centimeter across, functions as a bit. Thus, strings provide a means for the black hole's surface to hold the immense amount of information that fell in during its birth and thereafter.

String Theory

IT SEEMS, THEN, that the horizon is made of all the substance in the black hole, resolved into a giant tangle of strings. The information, as far as an outside observer is concerned, never actually fell into the black hole; it stopped at the horizon and was later radiated back out. String theory offers a concrete realization of black hole complementarity and therefore a way out of the information paradox. To outside observers—that is, us—information is never lost. Most important, it appears that the bits at the horizon are minute segments of strings.

Tracing the evolution of a black hole from beginning to end is far beyond the current techniques available to string theorists. But some exciting new results are giving quantitative flesh to these ghostly ideas. Mathematically, the most tractable black holes are the "extremal" black holes. Whereas black holes that have no electrical charge evaporate until all their mass is radiated away, black holes with electrical or (in theory) magnetic charge cannot do that; their evaporation ceases when the gravitational attraction equals the electrostatic or magnetostatic repulsion of whatever is inside the black hole. The remaining stable object is called an extremal black hole.

CASCADE OF VIBRATIONS on a string slows down and becomes visible if the string falls into a black hole. Strings are small enough to encode all the information that ever fell into a black hole, thereby offering a way out of the information paradox.

Ashoke Sen of the Tata Institute of Fundamental Research (TIFR) in Mumbai, India, showed in 1995 that for certain extremal black holes with electrical charge, the number of bits predicted by string theory exactly accounts for the entropy as measured by the area of the horizon. This agreement was the first powerful evidence that black holes are consistent with quantum-mechanical strings.

Sen's black holes were, however, microscopic. More recently, Andrew Strominger of the University of California at Santa Barbara, Cumrun Vafa of Harvard University and, slightly later, Curtis G. Callan and Juan Maldacena of Princeton University extended this analysis to black holes with both electrical and magnetic charge. These new black holes could be large enough to allow Goulash to fall through unharmed. Again, the theorists find complete consistency.

Two groups have done an even more exciting new calculation of Hawking radiation: Sumit R. Das of TIFR, with Samir Mathur of the Massachusetts Institute of Technology; and Avinash Dhar, Gautam Mandal and Spenta R. Wadia, also at TIFR. The researchers studied the process by which an extremal black hole with some excess energy or mass radiates off this flab. String theory fully accounted for the Hawking radiation that was produced. Just as quantum mechanics describes the radiation of an atom by showing how an electron jumps from a high-energy "excited" state to a low-energy "ground" state, quantum strings seem to account for the spectrum of radiation from an excited black hole. The information paradox is well on its way to being resolved. Windbag will be right.

The principle of black hole complementarity has received spectacular mathematical confirmation by Maldacena and others. Following the introduction by 't Hooft and myself of a so-called holographic principle, Maldacena discovered a powerful "holographic" equivalence between quantum gravity in a dimension called anti de Sitter space and a conventional quantum system. He gives a compelling argument that information in black holes in this space is never lost behind the horizon. As a result of Maldacena's work, physicists have made black hole complementarity one of the working assumptions of modern string theory.

Quantum mechanics, I believe, will in all likelihood turn out to be consistent with the theory of gravitation; these two great streams of physics are merging into a quantum theory of gravity based on string theory. The information paradox has played an extraordinary role in this ongoing revolution in physics. And although Goulash would never admit it, Windbag will probably turn out to be right: his recipe for *matelote d'anguilles* is not forever lost to the world. SA

MORE TO EXPLORE

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