

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 arch rival, Professor Goulash. The capsule contains the only copy of a vital mathematical formula, to be used by future generations. But Goulash's diabolical scheme to plant a hydrogen bomb on board the capsule 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. Why, the fiend has destroyed my formula and must pay. Off with his tenure!"

"Nonsense," says an unflustered Goulash. "Information can never be destroyed. It's just your laziness, Windbag. Although it's true that I've scrambled things a bit, 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.

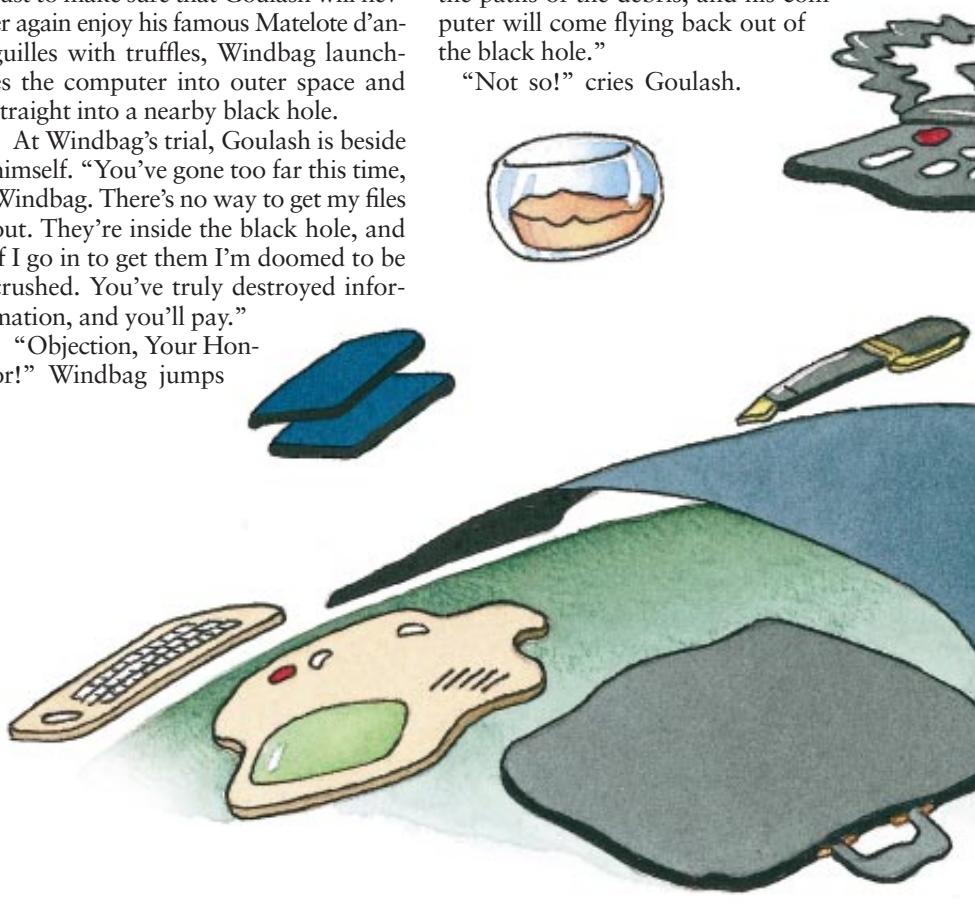
Windbag's revenge is equally diabolical. While Goulash is out of town, his computer is burglarized, along with all his files, including his culinary recipes. Just to make sure that Goulash will never again enjoy his famous Matelote d'an-guilles with truffles, Windbag launches the computer into outer space and straight into a nearby black hole.

At Windbag's trial, Goulash is beside himself. "You've gone too far this time, Windbag. 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 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. It's really no different from the bomb. 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.



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, as 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 black hole's center, where he becomes crushed.

"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 Einstein taught us that nothing can ever do that. There is no way the evaporation products, which come from outside the horizon, can contain my lost 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 hori-

zon, 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.

"Hawking is wrong," 't Hooft begins. "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 of this problem."

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

The Information Paradox

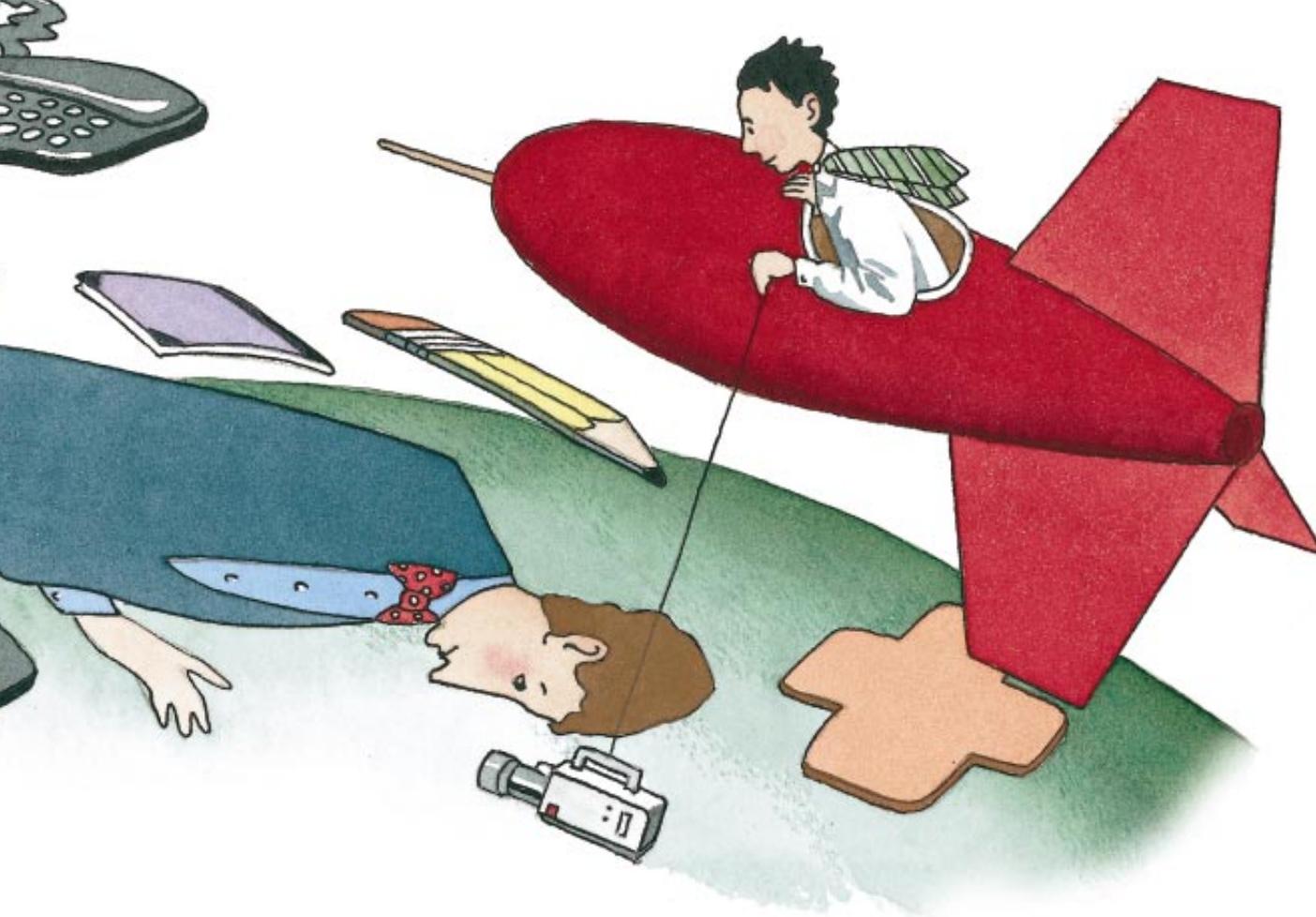
Windbag and Goulash are, of course, fictitious. Not so Hawking and 't Hooft, nor the controversy of what happens to information that falls into a black hole. Hawking's claim that

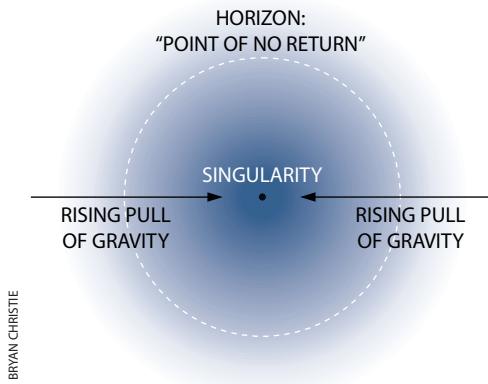
black hole consumes information has drawn attention to a potentially serious conflict between quantum mechanics and the general theory of relativity. The problem is known as the information paradox.

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 quantum 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, en-





BRYAN CHRISTIE

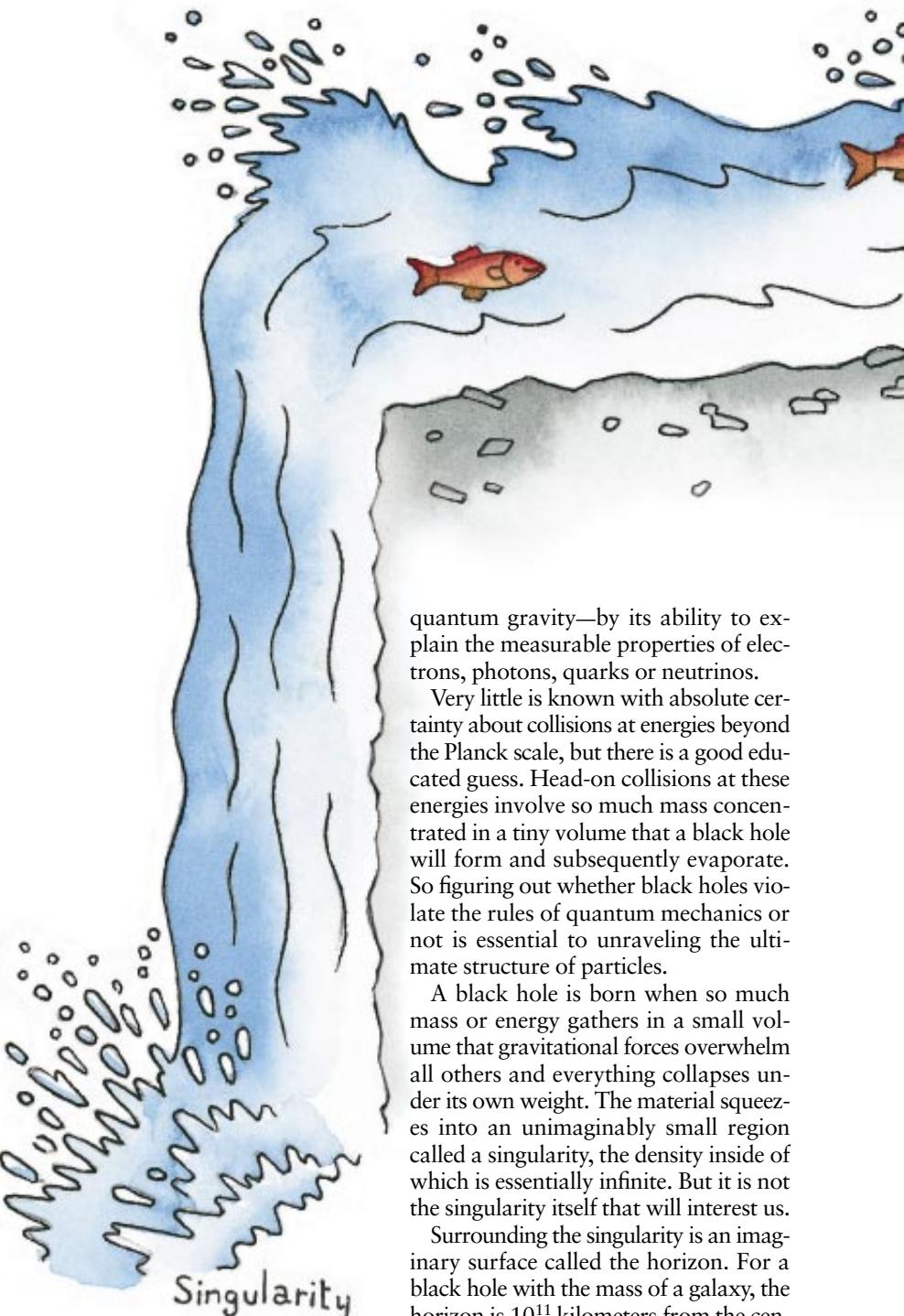
ergy may be created or destroyed, threatening one of the most essential underpinnings of physics. The conservation of energy is ensured by the mathematical structure of quantum mechanics, which also guarantees reversibility; losing one means losing the other. As Thomas Banks, Michael Peskin and I showed 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, like counting angels on pinheads. But it is not so at all: 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 they are not so ele-

INVISIBLE HORIZON is represented in this analogy as a line in a river. To the left of it, the water flows faster than a "lightfish" can swim. So 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 can never get back out; the object inevitably falls into the singularity at the black hole's center, but without noticing anything special about the horizon.



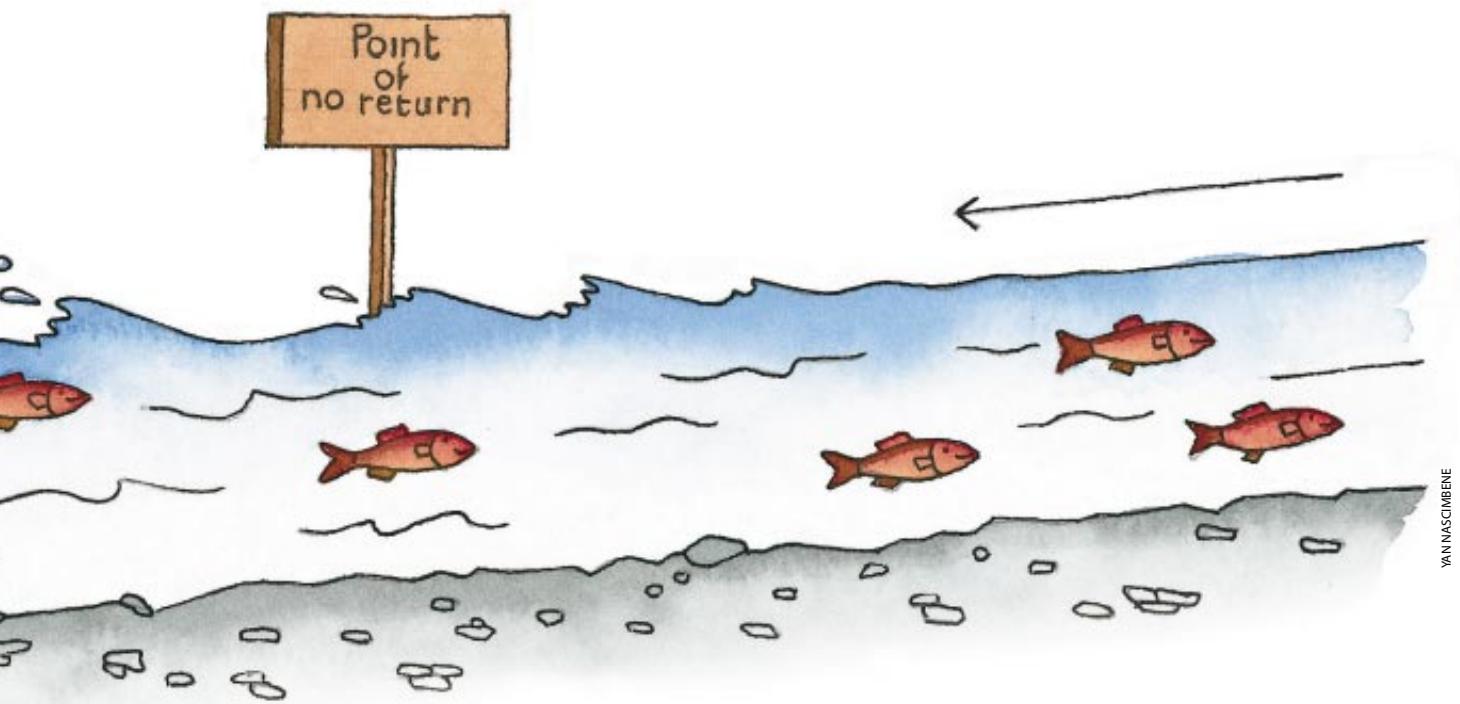
quantum gravity—by its ability to explain the measurable properties of electrons, photons, quarks or neutrinos.

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. But it is not the singularity itself that will interest us.

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 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.

mentary 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



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, one of the pioneers 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 past this point can never get back up. It is doomed to be crushed on the rocks below Singularity Falls, located farther 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. He checks his pulse with his wristwatch—normal. His breathing rate—normal. To him the horizon is just like any other place.

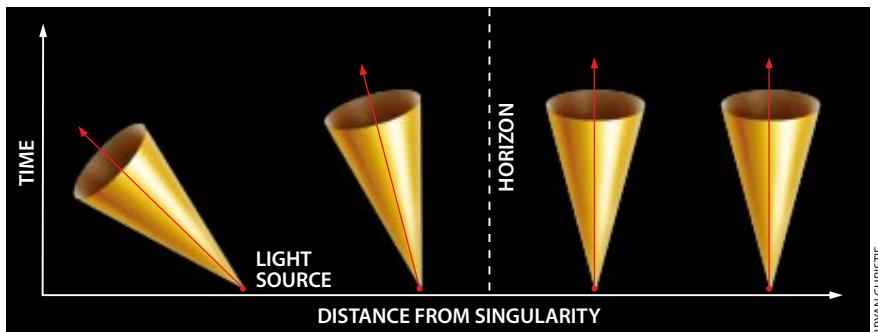
But Windbag, watching Goulash from a spaceship safely outside the horizon, sees Goulash acting in a bizarre way. Windbag has lowered to the horizon a cable equipped with a camcorder and other probes, to better keep an eye on Goulash. As Goulash falls toward the black hole, his speed increases until it 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 a strangely lethargic Goulash. As he falls, the latter shakes his fist at Windbag. But he appears to be moving ever more slowly; at the horizon, 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 strange-

ly, 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 in Israel. 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 just 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,



til 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 space-time locations. Black hole complementarity does away with even that.

How this principle actually comes into play is clearer when applied to the structure of subatomic particles. 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 cloud of negative charge. The electrons in the cloud move so rapidly they form a blur. But as the atom gets closer to the black hole, its internal motions seem to slow down, and the electrons become visible. The protons and neutrons in the nucleus still move so fast that its structure is obscure. But 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.)

Many physicists believe elementary particles are made of even smaller constituents. Although there is no definitive theory for this machinery, one candidate stands out as being the most promising—namely, 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

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

however, it registers higher temperatures. 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 can measure it.

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 very special for Goulash to completely miss them as he passes through.

The discovery of entropy and other 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 radia-

tion comes from the region of 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 the course of 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 un-

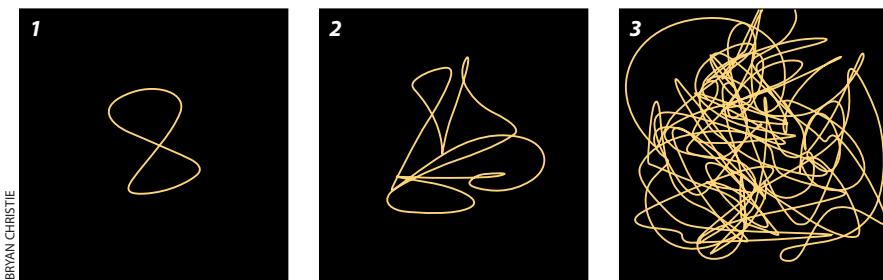
feathers that flap even faster. Soon these, too, would come into view, adding further to the apparent size of the bird. Windbag sees the hummer enlarge continuously. But Goulash, who falls with the bird, sees no such strange growth.

Like the hummingbird's wings, the string's oscillations are usually too rapid 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 Amanda Peet, Thorlacius, 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 that 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



CASCADE OF VIBRATIONS on a string slow down and become 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 and offer a way out of the information paradox.

horizon are minute segments of string.

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.

Following earlier suggestions of mine, Ashoke Sen of the Tata Institute of Fundamental Research (TIFR) 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. Unlike Sen's tiny black holes, these new black holes can 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.

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, which appears to be well on its way to being resolved, 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: the recipe for Mate-lote d'anguilles is not forever lost to the world.

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, to 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.

Further Reading

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- TRENDS IN THEORETICAL PHYSICS: EXPLAINING EVERYTHING. Madhusree Mukerjee in *Scientific American*, Vol. 274, No. 1, pages 88–94; January 1996.