Black hole

General relativity predicts that when a massive body is compressed to sufficiently high density, it becomes a black hole, an object whose gravitational pull is so powerful that nothing can escape from it. Such objects are of great astrophysical interest, as, for example, the presumed engines that power quasars. But apart from their astrophysical implications, black holes are of great intrinsic theoretical interest. Although in classical physics a black hole is unable to shed any of its mass, quantum effects allow it to *radiate* and lose energy. This black hole "evaporation" poses a great potential paradox. Nothing seems to prevent the black hole from radiating away all of its mass and disappearing completely. Thus, all information about the object from which the black hole formed seems to become forever inaccessible.

It is not yet firmly established that black holes really destroy information in this way. But if they do, we face the daunting task of finding a new conceptual basis for all of physics. Conceivably, the discovery of black hole radiance portends a scientific revolution as profound as those that led to the formulation of relativity and quantum theory in the early 20th century.

Black hole thermodynamics. In classical general relativity, a black hole can be characterized as a "region of no escape" bounded by a surface known as an "event horizon." Whoever falls through the horizon is unable to return to the region outside the black hole, or even to send any signal that can propagate to an observer outside. In fact, general relativity predicts that one who enters the black hole is inexorably driven to a "singularity," a region of infinite spacetime curvature and hence infinitely strong gravitational forces. The singularity signifies the breakdown of classical physics deep inside the black hole. Quantum effects become important there, and classical general relativity cannot predict what will happen.

The time–independent black hole solutions to the classical field equations of general relativity can be characterized by just a few parameters; a solution is uniquely determined once its mass, angular momentum, electric charge, and magnetic charge are specified. Thus, although the collapse of a star to form a black hole may be a very complex process, the end result is a remarkably simple object with very little structure. Once the collapsing body settles down to a stationary state, all detailed information about the body has become completely inaccessible to an observer who stays outside the black hole. “A black hole has no hair.”

In the case of a nonrotating, uncharged black hole, the event horizon is a sphere; its radius R is related to its mass M according to

$$R = \frac{2GM}{c^2} \ , \tag{1}$$

where G is Newton’s gravitational constant, and c is the speed of light. (R is defined by $A = 4\pi R^2$, where A is the area of the horizon.) Thus, a black hole of one solar mass has a radius of about 3 kilometers. According to the “area theorem” of general relativity, the total area of all event horizons can never decrease in any process involving any number of black holes. This result (along with conservation of energy) implies that a black hole cannot split up into smaller black holes. In classical general relativity, a (nonrotating) black hole is an absolutely stable object—it can accrete matter to become larger and heavier, but nothing can make it smaller and lighter. (Rotating black holes can lose energy by spinning down, which accounts for some of their interesting astrophysical effects.)

When quantum effects are included, this statement must be modified—a black hole can emit radiation and lose mass. In fact, semiclassical calculations show that the black hole emits like a thermal body with a characteristic temperature. For a nonrotating black hole of radius R, this temperature T is given by

$$k_B T = \frac{\hbar c}{4\pi R} = \frac{\hbar c^3}{8\pi GM} \ , \tag{2}$$

where k_B is Boltzman’s constant, and $\hbar$ is Planck’s constant. Thus, the typical radiation quanta emitted by the black hole have a wavelength comparable to R. For a solar mass black hole, the temperature is $T = 6 \times 10^{-8}\ {}^\circ K$.

Since the emission is thermal, a black hole surrounded by a radiation bath at temperature T remains in equilibrium—it emits and absorbs at equal rates. Although this equilibrium is actually unstable, emission or accretion of radiation at temperature T can nonetheless be regarded as a reversible thermodynamic process, and the entropy of a black hole can therefore be computed (up to an unknown additive constant). The result is

$$S/k_B = \frac{1}{4}\,\frac{A}{L_{\text{Planck}}^2}\ , \tag{3}$$

where A is the area of the horizon, and $L_{\text{Planck}} \equiv (\hbar G/c^3)^{1/2} \sim 10^{-33}$ cm is the "Planck length" that can be constructed

from the fundamental constants. Thus, the "area theorem" of classical general relativity can be regarded as a special case of the second law of thermodynamics, which says that entropy is always nondecreasing. Indeed, the analogy between the area theorem and the second law had inspired Jacob Bekenstein to anticipate eq. (3) (up to a then unknown multiplicative constant of order one) even before Stephen Hawking discovered that black holes radiate. The entropy of a black hole is truly enormous—about 10^{78} for a solar mass hole, some 20 orders of magnitude larger than the entropy of the sun.

Information Loss? The discovery of black hole radiance established a deep and satisfying connection between gravitation, quantum theory, and thermodynamics. But it also raised some disturbing puzzles. One puzzle concerns the interpretation of the black hole entropy. In other contexts, the statistical–mechanical entropy counts the number of *accessible* microstates that a system can occupy, where all states are presumed to occur with equal probability. If a black hole really has no (or very little) hair, the nature of these microstates is obscure. Eq. (3) invites us to construe the horizon as a quantum membrane with about one degree of freedom per Planck unit of area. But a more concrete conception of these degrees of freedom remains elusive.

Even more distressing is a serious paradox raised by Stephen Hawking. In his semiclassical calculation of black hole radiance, Hawking found that the emitted radiation is *exactly* thermal. In particular, the detailed form of the radiation does not depend on the detailed structure of the body that collapsed. This is because the radiance is induced by the gravitational field of the black hole *outside* the horizon, and the black hole has no hair that records detailed information about the collapsing body. While the semiclassical approximation used by Hawking is not exact, it is highly plausible that a more accurate treatment would still find that the emitted radiation is only very weakly correlated with the state of the collapsing body. The key constraint comes from causality—once the collapsing body is behind the horizon, it is incapable of influencing the radiation.

Thermal radiation is in a "mixed" state, not a "pure" state. This means that the state of the radiation cannot be precisely predicted; we can only assign probabilities to different alternatives. But according to the laws of quantum mechanics, if the initial state of a system is "pure" (precisely known), then the state remains pure at later times. Information is never destroyed *in principle* (although information often is lost *in practice*). An observer outside a black hole who detects the emitted radiation would recover little information about the body that collapsed to form the black hole. Since information is conserved in principle, this observer would conclude that most of the information about the initial body must be retained inside the black hole.

But suppose that the black hole continues to evaporate until it disappears completely. Then it seems that an initially pure quantum state, by collapsing to form a black hole and evaporating completely, has evolved to a mixed state. In other words, even if the initial state were precisely known, we are not able to predict with certainty what the final state will be. We can only assign probabilities to different alternatives. This is the "information loss paradox." The paradox is that if we try to analyze the evolution of a black hole using the usual principles of relativity and quantum theory, we are led to a contradiction, for these principles forbid the evolution of a pure state to a mixed state.

Hawking concludes that the usual rules of quantum mechanics cannot apply in all situations, which means that the fundamental laws of physics must be reformulated. Is there no way to escape this radical conclusion? It is conceivable that the semiclassical calculations are misleading, and that detailed information about the collapsing body really is encoded in the emitted radiation. But, as noted above, it is difficult to reconcile this possibility with causality, since the collapsing body is out of causal contact with the radiation once the body crosses the horizon.

Other ways of evading the paradox have been suggested, but all seem to have serious flaws. As a black hole evaporates and shrinks, it eventually becomes so small that the semiclassical picture of the evaporation process no longer applies. Our usual notions of causality, and indeed the very concepts of space and time, break down at distances comparable to L_{Planck}; at this distance scale, spacetime is subject to violent quantum fluctuations. Because these quantum gravity effects are not well understood, one is free to speculate about how a black hole with radius $R \sim L_{\text{Planck}}$ would behave.

Perhaps it stops evaporating, leaving behind an absoulutely stable black hole remnant. Such a remnant could serve as repository for most of the information about the collapsing body, thus resolving the paradox. But the cure may be worse than the disease. Since the initial black hole could have been arbitrarily massive, the remnant must be capable of carrying an arbitrarily large amount of information. This means that there must be an infinite number of species of stable remnant, all with size comparable to L_{Planck}, and mass comparable to the Planck mass $M_{\text{Planck}} = (\hbar c/G)^{1/2} \sim 10^{-5}$ g. Most likely, a theory that admits this kind of infinite degeneracy does not make sense, because the calculated rates for many otherwise plausible processes are found to be infinite.

Perhaps when the black hole shrinks down to the Planck size, the information that has been stored in it can finally leak out. But if the amount of information is large, it is impossible for it to come out quickly. There are fundamental limits to the amount of information that can be encoded in a Planck energy's worth of radiation in a finite time—the more information, the longer the time. So, there would need to be Planck size black holes that are arbitrarily long lived, even if no given species is absolutely stable. This scenario then runs into the same difficulties as the stable remnants.

Outlook. So far, all attempts to reconcile the evaporation of black holes with the conventional laws of physics have failed. It seems increasingly likely that the information loss paradox presages a new scientific revolution. The final outcome cannot now be safely predicted, nor can the depth of the revolution be clearly foreseen. But the puzzle of black hole evaporation remains one of the most important and challenging at the frontier of fundamental physics.

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