Science Fact

Black Holes and The Human Future

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1. A Taxonomy

What with the release of the first direct images of a black hole in the elliptical galaxy Messier 87 in 2019 and the 2020 Nobel Prize in physics shared for work on black holes by Sir Roger Penrose, Reinhard Genzel, and Andrea Ghez, the bête noire beloved of astronomers and astrophysicists is back in the spotlight again.

In some senses it never completely stepped out of that light. That's understandable, given that the popular perception of black holes tends toward the sensational and the apocalyptic. Consider just a few of the words and phrases traditionally used to describe them and their effects: "infinite densities," "infinite curvatures," "runaway gravity," "a monster swallowing everything," "trapped light," "spaghettification," "torn apart," "rip in the fabric of space-time," "no return."

The recent renewed presence of black holes nearer center stage in popular culture, however, casts that 1970s "monster" image of galactic gluttony and Void vacuum-cleaning in a new light. Our understanding of these holes in the sky has grown much more nuanced—particularly among the black hole theorists themselves, over the last twenty years.

This is not to say that black holes have grown kinder and gentler, exactly. They have, however, grown much more diverse in their theorized manifestations. For decades the most prominently discussed class of black holes were stellar-mass black holes, formed from the collapse of dying stars. Their masses run from about five to about eighty times the mass of the Sun, and the archetype of this class—Cygnus X-1, the earliest popular candidate for a black hole—weighs in reliably at about twenty-one times the mass of the Sun.

Although stellar black holes are still held to be the most common type of black holes in the Universe, the scientific descriptions of the dynamics, size, and formation routes for black holes have become much more varied over the last several decades. We now know that not only can the singular collapse of sufficiently massive stars lead to black hole formation and growth, but so can outright mergers—of existing black holes, or of black holes and neutron stars, or of pairs of neutron stars, or of just about any number of celestial permutations and combinations that exceed the threshold of the Tolman-Oppenheimer-Volkoff (TOV) limit (two to three solar masses).

Beyond stellar black holes, there are now also intermediate-mass black holes (IMBHs), tipping the scales from hundreds to about a hundred thousand solar masses and residing most commonly at the center of globular clusters. Supermassive black holes (SMBHs) of millions and billions of solar masses have also been found, residing most commonly at the center of galaxies both spiral and elliptical. Some astronomers refer to black holes of more than ten billion solar masses as “ultramassive black holes” (UMBHs) and black holes of more than one hundred billion solar masses as “stupendously large black holes” (SLABs).

Contrary too to our earlier static images of their fixed stellar afterlives, many black holes—even supermassive ones—have been found roving and wandering through space, and are not in any way “fixed” when it comes to location. Supermassives in the centers of giant elliptical galaxies (like that in Messier 87) apparently also grow from mergers not only of each of the two central galactic black holes of spiral galaxies, but also of those two holes’ entire associated “progenitor” galaxies.

The interplay between size, formation, and dynamic motion generates some problems for the picture sketched here, though. How, for instance, did very distant (and therefore very early) supermassive black holes form so soon after the Big Bang—when neither star formation nor accretion of matter would have occurred quickly enough for them to exist at that size and distance?

To the rescue come “primordial black holes” (PBHs). According to Stephen Hawking’s descriptions, PBHs originate not in the gravitational collapse of stars but in the special conditions prevailing less than a second after the Big Bang, during which timeframe local gas and dust could achieve such density as to skip stardom and go straight to black hole status.

Primordial black holes can occur across a very wide range of sizes and masses too, which addresses several problems at once. They can be far smaller than the threshold of visibility. At the other end of the size spectrum, PBHs can also be many thousands of solar masses in size. Originating in the very earliest moments of the Universe, they could easily have served as seeds for intermediate-mass black holes and for supermassive black holes.

All of this background sheds light on the increasingly ramified physical taxonomy of black holes. It also raises the possibility that, in combined forms both primordial, small, *and* wandering, black holes of manageable size might well manage to visit our Solar System, and may already have done so.

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2. Brute Force Energetics

So, what might we do when faced with a smallish primordial wandering black hole coming our way—besides running away? We *might* want to look at it as not only a bane but also a boon. A small mobile black hole that comes to *us* could be very convenient. We might make use of its properties, without having to first develop the technology of interstellar travel to go visit *it*.

The properties of such small, convenient black holes suggest an impressive list of intriguing applications: black hole lasers, black hole bombs, black hole starship drives, and black hole energy systems capable of powering entire technologically-advanced civilizations, to name just a few.

All of these applications are the result of another evolution in the scientific understanding of black holes that has led physicists to see them as neither static nor fixed—not only in terms of roving but also in terms of *spinning*.

The first modern model of black holes, stemming from the work of Karl Schwarzschild, presented black holes as static. Schwarzschild black holes have no angular momentum—like lilies of the field they do not toil, neither do they spin. They also do not possess electric charge, only mass (see the mass-only descriptors mentioned throughout this essay up to this point, and consider what those descriptors might be leaving out).

Kerr black holes, a later theoretical iteration, are a bit more realistic as they possess both mass *and* spin, though no charge. Kerr-Newman black holes, or charged black holes—a still later and yet more realistic iteration—demonstrate how a black hole in some ways fundamentally remains as simple as a particle, possessing only the physical characteristics of angular momentum, mass, and electric charge.

Angular momentum is so ubiquitous a trait in celestial bodies that it seems almost as if the Big Bang itself imparted spin to the many systems of our latter-day Universe. Thermodynamically, black holes that possess not only mass (a la Schwarzschild) but also charge and spin are far more likely to be "real" and actually exist in nature.

All of those hypothetical black hole applications mentioned earlier arise from a black hole possessing angular momentum. When a star implodes and shrinks (stellar-mass black hole formation) or peri-Big Bang gas and dust swirl together densely enough to skip the stellar step (primordial black hole formation), the spin already possessed by that star or those swirling particles of dust and gas speeds up—a *lot*—like ice skaters drawing in their arms as they rotate.

Work can be extracted from a spinning black hole's superfast rotation because that rotational energy is not inside the event horizon of the spinning black hole but outside it, in the region of spacetime called the *ergosphere* or *ergoregion*. There, the spacetime continuum is not only deformed but also "frame-dragged" along by the black hole as it rotates. The ergoregion exists between the event horizon (which one can travel around forever if one is moving at the speed of light) and the *ergosurface* (where one can forever avoid being frame-dragged if one is, again, moving at the speed of light).

Work can be extracted from the ergoregion via a number of mechanisms—particularly through Hawking radiation, the Penrose process, and the Blandsford-Znajek process. Each of these mechanisms involves a piece of matter such that, as that piece of matter nears the event horizon, it splits in two in such a way that one piece falls into the event horizon of the black hole. In the case of the rotating black hole, that infalling piece falls in the direction opposite the rotation of the black hole. In the instant when that piece of infalling matter passes through the event horizon, a kick is imparted to its outgoing "twin" such that the twin piece accelerates through the ergoregion or "escapes to infinity."

The acceleration kick for that escaping piece of matter is coupled to a minute but proportional slowing of the rotating black hole because energy is transferred from the angular momentum of the spinning black hole to the escaping particle or piece of matter. The escaping twin will have greater mass-energy than the original matter, while the piece fallen into the event horizon will have negative mass-energy.

Shoot light into a rotating black hole surrounded by a Dyson mirror-ball sphere, and the result will be superradiance. The light's photons are amplified or enhanced by the rotational energy they take from their passage through the ergosphere. They are further sped up as they bounce off the reflective surface of the mirror-ball and back through the ergosphere, then volleyed back to the reflective wall of the ball and back through the ergosphere, and back, and back, again and again. With each pass, more of that energy of angular momentum is imparted to the increasingly "enhanced" photons.

Repeat this pumping-up of radiant energy long enough and the resultant super-energetic radiation can be harvested to power civilizations. Or drive starships. Or be channeled into laser form, in a manner analogous to how the Penrose process and Blandford-Znajek process together explain how supermassive black holes can fire off gigantic relativistic jets across millions of light-years.

Or repeat until the superradiant scattering of the photons builds and builds—to the point that the ensphered system goes into runaway mode and, soon enough, explodes with the force of a supernova.

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3. Black Hole Cybernetics

These models of black holes and their potential technological applications are far removed from earlier descriptions of black holes as merely immovable objects of irresistible force. Yet, for all the undeniable powers of these newer models and potential applications, they are essentially forms of brute-force energetics.

Perhaps more intriguing is what so many black hole theorists have turned their attention to over the last twenty-five years: namely, what a black hole is—not only *physically* but also *informationally*.

In mathematics and physics, "duality" ("not only . . . but also") emphasizes two different points of view for looking at the same object. This may sound like merely the perceptual switching one engages in when looking at a Rubin Vase's "goblet face illusion" or focusing on a stereogram to raise an apparent 3D image from a 2D surface, but it's not. In the study of black holes, duality involves a good deal of heavy-lifting mathematics.

Let's circle back to those stripped down similarities of black holes and simple particles, passed over lightly earlier. Given other "duals" in math and physics, those macrocosmic and microcosmic similarities between black hole and particle seem likely to represent increasingly meaningful "coincidences."

Important mathematically substantiated duals include the deep relationship between gravity and quantum field theory (gravity-gauge duality) first conjectured in 1997 by Juan Maldacena, currently at the Institute for Advanced Studies, Princeton. In his discussion of the gravitational Anti-de Sitter space and quantum Conformal Field Theory (AdS/CFT), Maldacena conjectured that AdS and CFT in certain circumstances appear to be the same thing, looked at from two different points of view—relativistic physics and quantum physics.

In the mathematical models, complex quantum systems have features similar to gravity. Viewed via Maldacena's duality, black holes—previously thought to be creatures mainly of relativity and gravity—are seen to also be consistent with quantum mechanics. The AdS/CFT correspondence is also called a "holographic duality" because the relationship between the gauge and gravity theories on either side of that forward slash are like the relationship between a three-dimensional object and its hologram.

Maldacena and Leonard Susskind (Institute for Theoretical Physics, Stanford) describe a further dual with their slogan ER=EPR. If two black holes become entangled, they create an ER, an Einstein-Rosen "bridge"—a shortcut in spacetime predicted by general relativity and better known as a wormhole. EPR stands for the Einstein-Podolsky-Rosen particle entanglements that Einstein considered "spooky action at a distance."

ER=EPR suggests that *both* wormholes from entangled black holes *and* quantum entanglements of particles are in fact duals of each other—two manifestations, on very different scales, of the same topological idea. Such underlying entangled connectedness may well explain how the quantum and gravitational aspects of the physical world fit into each other, and *that* goes a long way toward resolving contradictions between quantum mechanics and relativity.

At this point, the duals begin to cascade. Gravity may be universal because entanglement is ubiquitous. Given that entanglement can produce structures in spacetime (once considered a "no go" possibility), space and time themselves can now be seen as emergent properties arising from quantum entanglement. In a related fashion, spacetime seems to arise informationally: from quantum bits, "It from Qubit."

As we move deeper, the duals grow *new* duals. Black holes appear to be both *gloss* and *matte* black. By "gloss" here I mean to suggest that in some sense all the depth is on the surface—all the information of the black hole's interior "bulk" is encoded and entangled in the surface area of its event horizon. (This echoes work by Bekenstein and Hawking emphasizing that information in a black hole grows by the event horizon's surface area, not by volume. Bekenstein's and Hawking's work also suggests that a simple code can also be understood as a 2D hologram—another dual.)

"Matte" is meant to take into account the fact that investigating the nature of the black hole's interior provides insights into how spacetime carries out the Universe's underlying code. The mathematics of quantum computing's quantum error-correcting codes have intriguingly also been found in the mathematics describing the interior bulk of black holes. In this light, holographic spacetime and quantum-error correction are arguably one and the same.

We have now clearly crossed over into the discussion of what a black hole is informationally, here. This is as it should be, given that the quantum and relativistic physics of black holes are increasingly reconciled via information theory.

This reconciliation-via-information isn't particularly new—it goes back at least to the 1970s and those investigations by Hawking and Bekenstein. Work published in 2016 by Adam Brown and colleagues from Stanford and MIT more recently re-energized interest in that information theory approach when Brown and his team included the conjecture that black holes produce complexity at the fastest possible rate allowed by physical laws.

Complexity's two aspects here are information storage and information processing, better known to computer scientists as memory and speed. As Thomas Hartman of Cornell noted in a 2016 review of the work of Brown et al, "the bound on memory is set by the thermodynamics of black holes in equilibrium, and the bound on speed is set by the dynamics of black hole interiors"—and these bounds "apply to any physical system." In essence, Brown et al conjectured that black holes are not only the fastest computers in the Universe; they are the fastest *possible* computers in the Universe.

Astronomers and astrophysicists may rightly object that the black holes that have been modeled in the mathematics are as yet too simplistic or idealized to be anything but toy models—and are very far away from black holes in the sky. Still, it's rarely smart to bet too heavily against the mathematics. Galileo didn't say the book of nature is written in the language of mathematics for nothing, after all.

We don't even have to specify the computers as quantum. Black holes can be described as Turing machines in the old-school information-processing sense too. A black hole's contents can serve as an inherently extensible machine "tape." Input could come from irradiating—with photons of appropriate energy, say—the particles inside the black hole, changing their states. The external observer functions as a moveable tape "head" that can shift the tape and read the machine's output, in the form of Hawking radiation.

Considering black holes as quantum computers, though, *does* have the advantage of bringing the information, quantum, and relativity realms still closer together.

As early as 2006, Seth Lloyd of MIT suggested that black holes could be used as quantum computers and we could essentially program a black hole by inputting the right collection of matter. This certainly has not yet been achieved. If we were in possession of a full theory of quantum gravity, however, we *would* arguably be able to program a black hole. Such programming would then cease to be a "physics problem" and become instead only an "engineering problem."

With this idea of programmable, information-processing black holes, we have moved beyond brute force energetics and on to black hole cybernetics.

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4. How To Hack a Black Hole

Given the growing consensus that black holes can process information, one must wonder: Why has no one seriously advanced the question of how to hack a black hole? Is there "merely" an engineering problem, or is this still a physics problem, too?

Recent work on the black hole information paradox suggests that information (in line with the quantum mechanical understanding of it) cannot be lost from the Universe, not even beyond the event horizon of a black hole. Information therefore must be able to somehow escape the black hole—that thing from which gravity prevents *everything* from escaping.

The key to understanding how to hack a black hole involves that "right collection of matter" Lloyd refers to. That matter is usually taken to be particles of Hawking radiation, the mechanics of which we touched on earlier in our "piece of matter" discussion of rotating black holes and brute force energetics. Somewhat later we also discussed the role of Hawking radiation as "output" from our black hole Turing machine.

Suffice it to say here, for our "black hole hack" thought experiment, that Hawking radiation is deeply entangled with the black hole from which it came. So deeply entangled that the interactions between a black hole and the radiation the black hole has emitted create a wormhole between the two—and a potential backdoor into the black hole itself. That wormhole likely plays a role in how the information in the black hole is not ultimately "lost" to the Universe.

That "back door" is also where the hack begins but not where it ends. The full description of the hack involves a quantum computer simulation—a physical system not so very different from what it simulates, in this case. If you collect the black hole's Hawking radiation, feed it into a quantum computer, and run a full simulation of the black hole, you get a very interesting strange loop.

In *simulating* (via that Hawking radiation) the original hole, the quantum computer also becomes *entangled* with that original black hole. Inside the simulation, the entanglement translates into a geometric link between the simulated black hole and the original black hole. That geometric link is, again, generally called a wormhole.

The wormhole connecting the black hole and its computer simulation, according to Hartman and others, is a *replica* wormhole, a sort of "disorder averaged" copy over all the wormholes existing between the physical black hole and its own Hawking radiation.

At this point we see a cascade in the types of wormholes. A wormhole can form between two black holes. Or between two entangled particles. Or between a black hole and its Hawking radiation. Or between a physical black hole and its simulation when the Hawking radiation from the original black hole is fed into a quantum computer simulation of that original black hole. All of these are arguably duals of each other.

The "replica" wormhole makes possible the hack from the simulated black hole in the quantum computer into the original black hole it is simulating. Via that wormhole we can shoot "photons of appropriate energy" into the simulated black hole, as input, changing the states of the entangled particles inside the original black hole the computer is simulating—state-changes that in turn can be read via the output of Hawking radiation, and that radiation looped again into the system.

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5. Simulations and Scenarios

Most of us don't deny that computers are steadily improving the resolution of the physical systems they can simulate, but some of us may object that what we're describing here seems to involve a huge category mistake—something on the order of saying a computer virus can give you a sinus infection.

Yet information theorists might, with some cause, contend that the *real* category mistake lies in believing that there is some foundational difference between a black hole in the Universe and a black hole simulated on a quantum computer. If information is the ultimate reality, then there is no fundamental difference between those two black hole manifestations.

One does not have to go that far to appreciate what the informational understanding of black holes might mean, should a roving primordial black hole—of a few Earth masses and the size of an orange, say—come rolling into the Solar System on an Earth-crossing trajectory.

In such an instance, rather than attempting to evacuate the Earth, or trying to move the planet, or trying to lever the black hole out of its threatening orbit via the laser-sail or kinetic-impactor approaches intended for the altering of asteroid orbits—rather than any of those, we might instead try to communicate with, command, and control that black hole.

Cybernetics means "the art of steering." We could do worse than using our knowledge of a black hole's informational nature to turn this impending bane and potentially apocalyptic inconvenience into a convenience and thorough-going boon—one that could provide us with great and unforeseen discoveries about the nature of the Universe itself, if we just have the foresight to approach it that way.

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