A Brief History of Black Holes

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Thought experiment: what would happen if you fell into a black hole? Let's pretend it's Cygnus X-1, the supermassive black hole located at the centre of the Milky Way. Approaching the black hole from a distance, you see a stream of white-blue fire roping a giant nearby star—a colossal orb of bright blue beyond the size or luminosity of any sun you've ever seen—into a burning maelstrom of gas, dust, and debris, a swirling accretion disc whose contents are heated to millions of degrees by the friction caused by the gravitational forces of the immense void at their centre. Protruding from the middle of this flaming whirlpool are great flashing spindles in which jets of matter and X-rays are violently emitted from the disc at a velocity near the speed of light, travelling for more than fifteen light-years before ballooning into an inflated bubble that expands at 225,000 miles per hour and has been doing so for a million years already. Past the vortex generated by the black hole, spinning eight hundred times per second, you see the first photon sphere rotating in the opposite direction to the vortex, and then, mere kilometres from the black hole itself, the second photon sphere rotating in the same direction as the vortex. Closer now, these luminous halos ringing your head are caused by light-particles spiralling towards or, if they're lucky enough to have sufficient energy to escape, away from the centre of the black hole. Even light, which moves at the maximum speed anything in the Universe may travel, is by the sheer force of the black hole's gravitational pull bound and bent into unstable orbits[1].

Looking out from this lower sphere, your vision is divided: below, complete darkness—for light rays cannot cross the black hole beneath you—whilst the upper half of your vision encloses the entirety of the sky. The line separating black from light is the photon sphere but, since the photons here are constantly circling, the light from all stars at all points in the sky is available to you; it is as if you are seeing simultaneously through the front of your eyes and the back of your head, a 360-degree perspective in which you can see even the stars behind you. Now you approach the black hole. To an outside observer, your every advance towards the black hole becomes slower and slower, whilst your body turns redder and darker and redder and darker until, arriving at the precipice of the black hole's event horizon, time finally stands still[2]. Your body has become black and is paralysed—from all external perspectives, you will be permanently fixed in this stasis. But time moves differently for you. Falling into the black hole in what seems to be normal time, you turn to look back at the world you're leaving and watch as a temporal acceleration takes place and the entire Universe ages and withers and dies in a fast-forwarded movie, transporting you to the very end of time. Now you are inside its darkness and there are no paths, no exits, leading away. Every step you take leads you further towards its centre. And the final thing you see is the last image of the dying star before its complete collapse, transfixed in space and time—here, within the warped infinitude of slow time, your eyes are filled with pure starlight, the incandescent whiteness of eternity's dome, forever frozen.

Now that the space odyssey is over, some qualifications are needed! Firstly, as far as our thought-experiment is concerned, the tidal forces of a black hole's gravity would tear you limb from limb before you reached its surface[3]. Secondly, the jury's out on just what exactly you would be able to see inside the black hole, since general relativity tells us that the core of a star collapses into a single spatial point with zero volume, a singularity, but quantum mechanics renders such singularities impossible. We should also probably define exactly what a black hole is. A star is born when molecular clouds and gaseous nebulae of primarily hydrogen, but also helium and traces of heavier elements, begin to collapse; their

[1] Due to the masslessness of light, it cannot orbit anything in a stable way—unlike planets, which are able to orbit stars indefinitely. Light must eventually either spiral inwards or spiral outwards.

[2] In fact, time slows so much that, for an outside observer, it takes eternity for the infalling person to actually reach the edge of the black hole. Eventually, though, the infalling body will appear perfectly frozen in place.

[3] The technical term is 'spaghettification'—no, really.

gravitational attraction creates so much heat that hydrogen is converted into helium through nuclear burning—this is what makes the sun shine. A star dies when it has exhausted its nuclear fuel, but certain massive stars that expand into huge red giants can explode in tremendous supernovae, sending out shockwaves that violently compress their cores to create a mass with such compact density that an inescapable gravitational field is born: a black hole.

Thanks to Einstein, we now know that space is not a flat, empty vessel in which matter merely exists, as Newton once thought, but rather space itself bends—and time itself warps—wherever there is matter. Furthermore, this space-bending and time-warping are the *sole* effects of gravity: the distortion of spacetime that occurs near any object with mass. Picture a stretched sheet of rubber (space), then place a heavy object like a billiard ball at its centre (a star), and the dip in the rubber represents the gravitational field generated by the mass of a star which curves and warps the space around it. Nothing moves faster than the speed of light and, in a vacuum, light travels in a straight line. But if you now roll a marble (light) in a straight line across that rubber surface, you'll find that the marble is attracted towards the dip: since the star bends space around it, that bending, which is its gravitational field, causes light to be pulled towards it. Since light travels so fast, however, there simply isn't enough time for gravity to bend it as it would for slower-moving objects; the only way to bend light into a circular orbit is to have an immensely heavy object in an immensely small region. That's why the photon spheres we saw earlier only occur at black holes: only black holes sustain gravitational fields powerful enough to trap light itself, hence their name. As no light can reach us from these objects, they are effectively invisible.

How then do we know that they are there? The speed of light is the maximum allowable speed of information, wherein information is defined simply as the property of an object that can distinguish that object from anything else, and what we call the 'event horizon' refers to the furthest place to which information about an event could have travelled. It is a boundary in spacetime—a spatial surface at a point in time—beyond which a given event cannot yet communicate information[4]. Since the gravity of a black hole constrains light, no information can ever escape. A black hole can even be defined simply as the event horizon of an event whose extreme gravity renders it unknowable to anyone on the outside[5]. When you enter the black hole's event horizon, its gravity causes an infinite warping of time so that, to outside observers, it would take you an infinite amount of time to enter the horizon—your image becomes frozen on the boundary—whilst the 'gravitational redshift'[6] caused by the slowing of time and stretching of space by the black hole shifts the wavelengths of light into the red-end of the spectrum, hence your apparent redness to the observer. It is this infinite time-warping that also explains why, for you, the Universe appears to age infinitely. In actuality, though, black holes don't live for eternity: when they run out of celestial bodies to feed upon, they slowly evaporate by expelling the galactic food they've been digesting as what is called 'Hawking radiation', like a gigantic stomach belching itself out of existence.

Nevertheless, we do know black holes are there because we can infer their existence from the motion of stars, planets and light, which are dramatically bent towards a seemingly empty region of space. Just this week, in fact, we have witnessed the first observation of two black holes merging and the first measurement of the gravitational waves predicted by Einstein—in our analogy, stellar events violently warp the rubber sheet, stretching and contracting the spacetime fabric, which sends gravitational waves rippling across the wide pond that is our universe. Yet black holes have also remained a rather stubborn problem for physicists. All objects contain information, and the entropy[7] of an object is effectively its information-storage capacity. Since the second law of thermodynamics states that the entropy of the

[4]Information can travel at no more than the speed of light and can emanate in all directions, so an event horizon is a spherical surface which expands at the speed of light. Even if information isn't being purposefully or knowingly sent from an event, we can still define this expanding sphere of *possible* influence. Outside of an event horizon, it is therefore impossible to know anything about the event, or even if an event happened.

[5]Of course you can, in theory, go inside the black hole and find out what's happening, but then you can never get out again or even send a signal outside of the black hole, so *outside observers* remain ever clueless.

[6]Gravitational redshift is like a visual, gravitational version of the Doppler effect that causes sirens to sound higher in pitch when the vehicle is moving towards you and lower when moving away from you: the closer you are to a large mass, the larger your apparent wavelengths become, so the redder they appear.

[7]Entropy is a profound concept in physics with many interpretations and is fundamental to the theory of information. It characterises the 'chaos' of a system, as well as its capacity to store information and the 'usefulness' of its energy.

Universe may never decrease, black holes must store the entropy of the objects they consume. In fact, the mathematics hints that the entropy of a black hole derives not from its volume—as might be expected if the black hole was merely storing objects with entropy—but from its surface size, so the surface is somehow more 'real' than what's inside it. We consequently think that tiny fluctuations on the event horizon of the black hole encode the swallowed objects' information, which is somehow 'painted' onto the black hole's surface. However, another pesky problem is that, since black holes eventually evaporate and disappear and quantum mechanics requires that information cannot be destroyed, black holes seem to be physics-defying information-destruction machines!

Luckily, this 'information paradox' was solved only a month ago by Andrew Strominger, Stephen Hawking and Malcolm Perry. The black hole's event horizon, like all event horizons, expands at the speed of light[8]. Within that horizon are rays of light unable to escape its gravity but necessarily travelling at the speed of light too, such that for every point on the horizon there is a light ray. Imagine the event horizon as a sphere of infinitely long straws. Since these straws increase in length at the speed of light, the limit of how fast information can travel, these straws are effectively isolated from one another. Black holes are often consuming objects and, when a particle enters the event horizon, its mass induces a tiny gravitational field—a zero-energy gravity-particle called a 'soft graviton'. Each soft graviton warps the spacetime within the black hole a minute amount, causing a 'supertranslation' that can move straws up and down or back and forth. These tiny gravitational fluctuations are called 'soft hairs' and their zero-energy causes them to spread out over an infinite amount of space[9]—but the boundary of the black hole, due to extreme spacetime warping, is itself infinitely far away, so hairs can only ever reach the maximal boundary of this isolated spacetime: the event horizon. Every time a particle enters a black hole, onto this 2D surface soft hairs are painted, which, as pieces of gravity, create tiny warps in spacetime, such that the Hawking radiation emitted from the black hole is distorted in such a way as to encode the information from the original particle onto the altered trajectory of departing radiation. Whilst such encoded information is unreadable, these soft hairs are the ghostly gravitational fingerprints for a memory bank of practically-lost but scientifically-conserved information.

Whilst there are still a few thorny questions to be answered, the solution to the information paradox connects to another profound physical theory. The black hole's surface is a two-dimensional object, yet all the information of three-dimensional objects seemingly inside its volume is mapped by the hairs on its surface. Thus, black holes are like holograms: 2D representations of 3D objects. Within string theory[10], the 'holographic principle' suggests that our very universe might function like a black hole, in which all 3D objects are simply low-energy shadows of 'true' objects painted on a 2D boundary at the edge of the Universe, the result of cooling effects after the Big Bang. Why is all this of interest to the public? Firstly, we need to know if Plato was right all along—what if humans are looking at the insubstantial shadows on the cave's wall and turn out to be prisoners of truth's second-order projections? Secondly, enterprises like the Hubble Heritage Project and the ongoing research into black holes creates new sources of beauty for the public and takes us to the very edges of our reason through blindingly brilliant aporias that expand our range of sublimity. Finally, we continue to study black holes because of the revelations of reality it delivers, so that one day we will be able to say, in the words of Carlo Rovelli: "Another veil has fallen".

[8]What *is* special about a black hole event horizon compared to any old event horizon is that space and time are so warped that the event horizon appears to stand still in space for any outside observer: black holes don't get bigger (unless they swallow something). If you were inside the black hole, however, you *would* experience the event horizon expanding at light-speed. It's akin to a gravitational TARDIS: finite and stationary on the outside—and infinitely-large and ever-expanding on the inside!

[9]This is due to the Heisenberg uncertainty principle in quantum mechanics: the more well-defined a particle's momentum is, the less well-defined its position is. Here is the extremal case where the momentum is precisely known (zero), so the particle is located everywhere at once.

[10]A candidate for a 'theory of everything' that may be able to describe, for example, what happens at the centre of a black hole. It models particles as tiny strings rather than infinitesimally-small points.