The End of Time

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A piece on the 2020 Nobel Prize in Physics for interested laypeople. Publication outlet TBA!

Albert Einstein is best known for his theory of *special relativity*: a Dalí-esque realm where clocks melt, long poles fit into short barns, and mass equals energy. But his best was yet to come. In 1915, Einstein formulated *general relativity*, succeeding Newton's theory of gravity in the same way special relativity succeeds Newtonian mechanics. Elegantly connecting physics and geometry, it is, by many accounts, the most beautiful scientific theory ever devised. In John Wheeler's maxim,

Spacetime tells matter how to move.
Matter tells spacetime how to curve.

A large mass like the sun curves spacetime like a bowling ball deforms a rubber sheet. Planets execute their circular orbits not because a mysterious force pulls them through space, but because they roll like marbles along a curved geometry (Fig. 1).

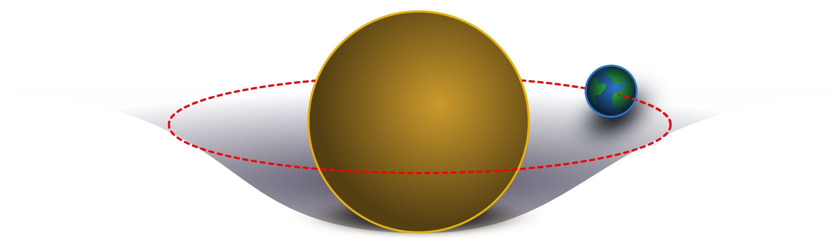

Figure 1. The sun bends spacetime like a bowling ball on a rubber sheet.

Whatever its aesthetic appeal to the initiate, physicists of the day found general relativity forbidding and uselessly precise. Experimentalists could not test it against Newtonian gravity until 1919, when Arthur Eddington observed starlight deflected around the sun during a solar eclipse. Theorists were daunted by its formidable mathematical prerequisites. Einstein was evidently 40 years ahead of his time.

The one major breakthrough, prior to the 1950s, was a curious discovery made on the Russian frontlines a few weeks after Einstein presented his results. Karl Schwarzschild, a German astrophysicist and artillery officer, solved Einstein's equations exactly to determine how a sphere of matter dimples the spacetime around it. The answer was sensible, reducing to Newtonian trajectories when masses are small. But for a very dense sphere, two surprises emerged: first, there is a *light-trapping region* around the sphere; second, if the sphere is contracted to a point, spacetime in the vicinity curves so dramatically that general relativity itself breaks down (Fig. 2). This is called a *singularity*, mathematical parlance for "disaster". Schwarzschild died of pemphigus a year later, but bequeathed to the world the enigma of black holes.

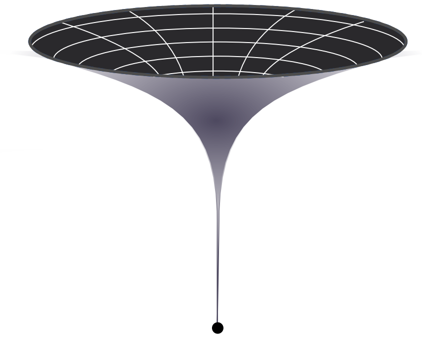

FIGURE 2. A Schwarzschild black hole and its singularity.

Einstein admired the simplicity of Schwarzschild's solution, but was uncomfortable with its implication that *time itself* ended inside the black hole. He would later argue that the singularity was an artefact, a bug coming from the assumption the geometry was perfectly spherical. It would disappear, he concluded, "in the real world", where symmetries were harder to come by and matter would strenuously object to being contracted to a point. The maestro had spoken, and for many physicists, that settled the matter.

In 1964, almost 50 years after Schwarzschild's discovery and 10 years after Einstein's death, a professor of mathematics crossed a busy London street. An impression flashed into his mind—a skin of light, pulsing outwards and *getting smaller*—but he lost it again in the hustle and bustle of midday traffic. The course of 20th century physics might be very different if he had not, by luck, recalled it the following day. The professor was Roger Penrose, and his mental image would inspire the most important technical development since Schwarzschild: the *Penrose singularity theorem*, a mathematical result showing that singularities are not mere bugs arising from symmetry, but inevitable features of a curvy universe.[1] It is perhaps a mercy Einstein did not live to see the most elegant theory ever devised, the apotheosis of his genius, robustly predict its own demise.

Penrose shared the 2020 Nobel Prize in Physics with Andrea Ghez and Reinhard Genzel, astronomers who independently confirmed the existence of a supermassive black hole at the centre of our galaxy. Penrose made their work possible by convincing the world that black holes exist. If Einstein's prejudice still held sway, no one would devote a career to looking for them! The starting point of Penrose's argument is that *gravity is attractive*, focusing light like a magnifying glass. If light rays are already converging, gravity cannot pry them apart and they will collide (FIG. 3). Penrose's flash of inspiration, as he crossed the street, was the notion of a *closed trapped surface*: a complete surface like a sphere, with an inside and an outside, such that light heading *outwards* from the sphere converges. It may sound impossible for outgoing light rays to get closer, but this is exactly what happens in the light-trapping region of a black hole.

Since gravity is a magnifying glass, rays going either outwards or inwards from the closed trapped surface will collide with each other. We can picture this scenario in two dimensions (FIG. 5), with space initially on the horizontal axis and time on the vertical axis. The closed trapped surface is represented by two points, with an inside (a dotted black line) and an outside

[1]A year later, a bright young PhD student called Stephen Hawking would run Penrose's arguments in reverse, and find a singularity at the beginning of time we call the Big Bang.

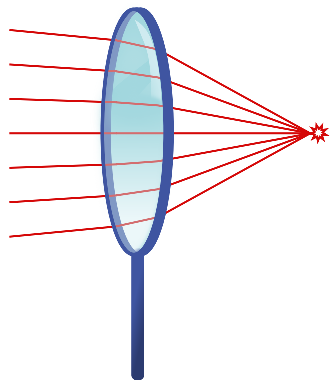

Figure 3. If rays are already converging, gravity focuses them like a magnifying glass.

(solid black line). The darker rays head outwards from the surfaces, and the lighter rays head inwards, both colliding at some point.

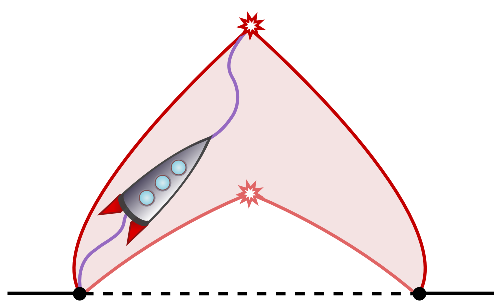

Figure 4. Time runs out at the top of the blob.

Penrose showed carefully that the *future* of the trapped surface—the region that can be reached by a spaceship starting at one of the black dots—is the pink blob between light rays. It is finite, and cannot be extended. To see why, imagine that a light ray is allowed to pass through a collision. There will be a point on the extended ray which can be reached by a "zig-zag" light ray path which swaps between rays. The kink in this zig-zag path can be smoothed out, like pulling on a crimped thread, to form a *shorter* path that a very fast rocket ship could use to arrive at the same point. And because rocket ships can always be a little slower, or a little faster, this path can be varied to give a small ball of points accessible by rocket. Crucially, this zig-zag argument (Fig. 5) shows that a rocket can visit any point on an extended ray.

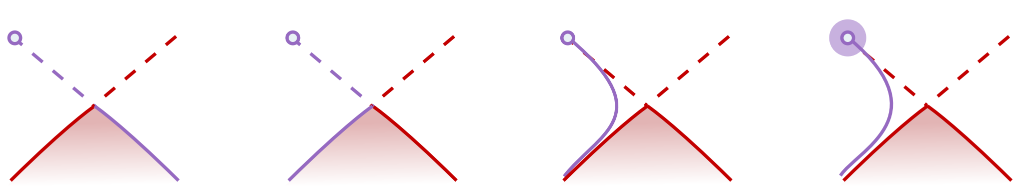

Figure 5. A point on an extended ray can also be reached by a zig-zag path which switches rays at the collision. This zig-zag can be smoothed into a shorter path a rocket could take, and varied slightly to visit nearby points.

Penrose realized that this was impossible. Since nothing can travel faster than light, and rockets are strictly slower, the *edge* of the future consists of points reached only by light ray. If we draw a little ball around such a point, then by definition of edge, part of it must fall outside, as shown in Fig. 6. If a rocket could reach such a point, we could vary the rocket's speed to reach a ball of nearby points; this is illegal, so only light rays, whose speed cannot be varied, are allowed to get there. The zig-zag argument tells us that any point on an extended light ray can be reached by rocket, so *no extended ray is on the edge of the future*. Penrose concluded that, since the future must have an edge (rockets can't go everywhere!), and there are no other light rays to provide it, the future must end in a singularity at the top of the blob.

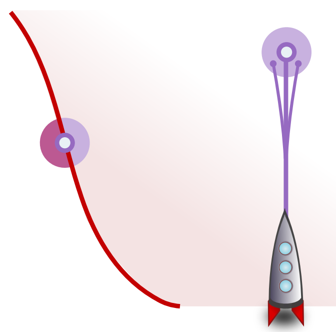

Figure 6. On the left, a point on the edge of the future. Any small ball around it lies partly outside. On the right, a point in the interior of the future, surrounded by a ball of rocket-accessible points.

In contrast to Schwarzschild's perfect sphere, a closed trapped surface can be puckered, deformed, and filled with matter; the singularity will form regardless. Evidently, the bugs are not in in Schwarzchild's mathematics, but Einstein's beautiful theory. Whether singularities are truly bugs in Nature, or are somehow smoothed away by new physics, remains to be seen. But as Penrose's fellow laureates discovered, black holes—Schwarzschild's legacy and Einstein's embarrassment—can be found in our galactic backyard.