The End of Time

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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*, superseding Newton's theory of gravity in the same way special relativity supersedes 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 deforming 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).

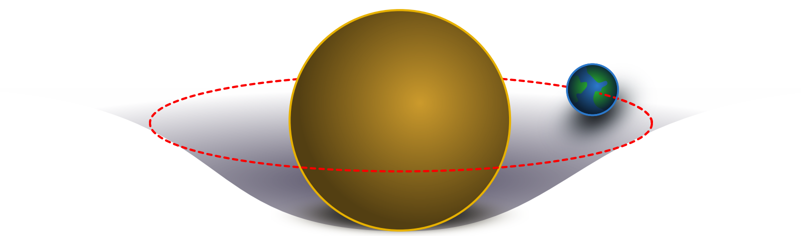

Figure 1. The sun bends spacetime like a bowling ball on a rubber sheet.

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 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 emerge: first, there is a *light-trapping region* around the sphere; second, if the sphere is contracted to a point, spacetime in the vicinity is curved 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.

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

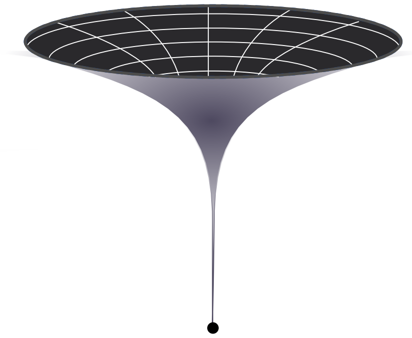

Figure 2. A Schwarzschild black hole and its singularity.

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 are 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 him to define what is called a *closed trapped surface*. It motivated 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. 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.

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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 convex lens. 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 the spheres of light pulsed out from the sphere, and into its interior, *both* get smaller. 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 convex lens, both sets of rays will collide, a scenario we can most easily picture in two dimensions (Fig. 4). The closed trapped surface is represented by two points, with an inside (a dotted black line) and an outside (solid black line). The dark red rays which head away from the interior are focused at some point, while the light red rays heading inwards converge sooner. Penrose showed carefully that the *future* of the trapped surface—the region

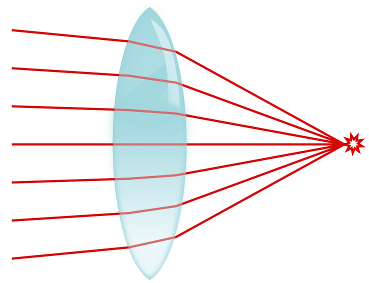

Figure 3. If rays are already converging, gravity focuses them so they collide.

that can be reached by particles starting at either of the two black dots—is the pink blob between light rays. It is finite, and cannot be extended. For observers unlucky enough to be stationed at the trapped surface, time itself ends in a singularity at the top of the blob.

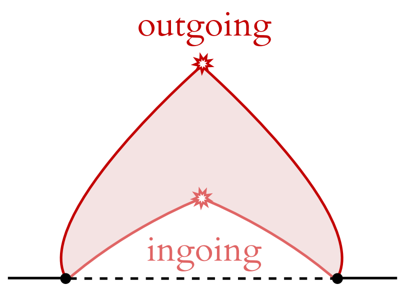

Figure 4. The end of the future for a closed trapped surface.

Unlike Schwarzschild's solution, a closed trapped surface is generic: it makes no assumptions about symmetry, only that gravity is an attractive force. Not only are these surfaces generic, but astrophysically relevant, since they can form in collapsing stars. Evidently, the bugs are not in in Schwarzschild's mathematics, but general relativity itself. Whether singularities are a bug in Nature remains to be seen, since a *quantum* theory of gravity may save time from its destruction at the hands of geometry. But as Penrose's fellow laureates discovered, black holes—the disquieting legacy of Karl Schwarzschild—can be found in our galactic backyard.