The brain requires an immense amount of blood, oxygen and energy, and going even a few minutes without these vital support systems is thought to cause irreparable damage.

Since the early twentieth century, scientists have conducted experiments that keep animals' brains alive from the moment the heart stops, by cooling the brains and pumping in blood or a substitute. But how well the organs functioned afterwards is unclear[2]. Other studies have shown that cells taken from brains long after death can perform normal activities, such as making proteins[3]. This made Yale neuroscientist Nenad Sestan wonder: could a whole brain be revived hours after death?

Sestan decided to find out — using severed heads from 32 pigs that had been killed for meat at a slaughterhouse near his lab. His team removed each brain from its skull before fitting the organ with a catheter. Four hours after death, the scientists began to pump a preservative solution into the brain's veins and arteries.

The system, which the team calls Brain*Ex*, mimics blood flow by delivering nutrients and oxygen to brain cells. The preservative solution also contained chemicals that stop neurons from firing, to protect them from damage and to prevent electrical brain activity from restarting. Despite this, the scientists monitored the brains' activity throughout the experiment and were prepared to administer anaesthetics if they saw any signs that the organs might be regaining consciousness.

The researchers tested how well the brains fared during a six-hour period. They found that neurons and other brain cells had restarted normal metabolic functions, and that the brains' immune systems seemed to be working. The structures of individual cells and sections of the brain were preserved — whereas cells in control brains that did not receive the preservative solution collapsed. And when scientists applied electricity to tissue samples from the treated brains, they found that individual neurons could still carry a signal.

But the researchers never saw coordinated electrical patterns across the entire brain that would indicate sophisticated activity. They say that restarting such function might require an electrical shock, or preserving the brain in solution for an extended period to allow cells to recover from any damage they sustained while deprived of oxygen.

Sestan, who has used the system to keep pig brains alive for up to 36 hours, has no immediate plans to try to restore electrical brain activity. His goal is to find out how long his team can sustain an isolated brain's metabolic and physiological functions.

"We just flew a few hundred metres, but can we really fly?"

"It is conceivable we are just preventing the inevitable, and the brain won't be able to recover," Sestan says. "We just flew a few hundred metres, but can we really fly?" Brain*Ex* is far from ready for use in people, he adds, not least because it is difficult to use without separating the brain from the skull.

Still, the development of technology with the potential to support sentient, disembodied organs has broad ethical implications for animals and people. "There isn't really an oversight mechanism in place for worrying about the possible ethical consequences of creating consciousness in something that isn't a living animal," says Stephen Latham, a bioethicist at Yale who worked with Sestan's team. He says that doing so might be justifiable in some cases — for instance, if it enabled scientists to test drugs for degenerative brain diseases on the organs, rather than on people.

The latest study also raises questions about whether brain damage and death are permanent. Lance Becker, an emergency-medicine specialist at the Feinstein Institute for Medical Research in Manhasset, New York, says that many physicians assume that even minutes without oxygen can cause fatal harm. But the pig experiments suggest that the brain might stay viable for much longer than previously thought, even without outside support. "We may have vastly underestimated the ability of the brain to recover," Becker says.

That could have consequences for organ donation. In parts of Europe, emergency responders who cannot revive a person sometimes preserve organs for transplantation by pumping oxygenated blood through the body — but not the brain. If technology such as Brain*Ex* becomes widely available, the ability to extend the window for resuscitation could shrink the pool of eligible organ donors, says Stuart Youngner, a bioethicist at Case Western Reserve University in Cleveland, Ohio. "There's a potential conflict here between the interests of potential donors — who might not even be donors — and people who are waiting for organs," he says.

In the meantime, scientists and governments are left to navigate quandaries related to the possibility of creating a conscious brain without a body. "This really is a no-man's land," says Koch. "The law will probably have to evolve to keep up." He wants a broader ethical discussion to take place before anyone tries to induce awareness in an isolated brain. "It is a big, big step," Koch says. "And once we do it, it's impossible to reverse it." ■ SEE COMMENT, P.299 & P.302

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ASTROPHYSICS

Black hole imaged for first time

Picture created by Event Horizon Telescope is one of the strongest confirmations yet of Einstein's general relativity.

BY DAVIDE CASTELVECCHI

Astronomers have finally glimpsed the blackness of a black hole. Using a global network of radio telescopes, they have for the first time produced a picture of an event horizon — a black hole's perilous edge — against a backdrop of swirling light.

"We have seen the gates of hell at the end of space and time," said astrophysicist Heino Falcke of Radboud University in Nijmegen, the Netherlands, at a press conference in Brussels on 10 April.

The picture, created by the Event Horizon Telescope (EHT) collaboration, made the front pages of newspapers around the world. Scientists hailed it as a historic achievement — and one of the strongest confirmations yet of Albert Einstein's general theory of relativity.

The image of a glowing, ring-like structure shows that a supermassive black hole 6.5 billion times the mass of the Sun lies at the centre of the galaxy M87, around 16 megaparsecs (55 million light years) away. The 'shadow' at its centre contains the event horizon, a spherical surface that represents a point of no return.

The results, comparable to recognizing a doughnut on the Moon's surface, were unveiled by the EHT in seven press conferences on four continents. The findings were published in *The Astrophysical Journal Letters*[1–6].

"When I was a student, I never dreamt that anything like this would be possible," says astrophysicist Roger Blandford at Stanford University in California. "It is yet another confirmation of general relativity as the correct theory of strong gravity."

Event horizons are the defining feature of black holes. To a nearby observer, they should appear as spherical surfaces shrouding their interiors from view. Because light can cross the surface only one way — inwards — the globe should look completely black.

The event horizon should appear five times larger than it is, because the hole warps space and bends the path of light. The effect, discovered by physicist James Bardeen at the University of Washington in Seattle in 1973, is similar to how a spoon looks larger when dipped into a glass of water. Moreover, Bardeen showed that the black hole would cast an even larger 'shadow'. This is because, at a certain distance from the event horizon, most light rays bend so much that they effectively orbit the black hole, forming a 'photon ring'.

COMBINED EFFORT

Radio astronomers calculated that to resolve details on the scale of even the largest known black holes, they would need to use short radio waves of around 1 millimetre wavelength — longer waves would produce a blurry image. Even so, because a telescope's resolution is proportional to its size, the feat would require a telescope the size of Earth. Astronomers turned to a technique called interferometry, in which multiple telescopes far apart from one another are pointed at the same object simultaneously. The telescopes work like shards of one big dish.

Various teams refined their techniques, and retrofitted some major observatories to add them to a network. In particular, a group led by Shep Doeleman, now at Harvard University in Cambridge, Massachusetts, adapted the 10-metre South Pole Telescope and the US$1.4-billion Atacama Large Millimeter/submillimeter Array (ALMA) in Chile to do the work.

In 2014, Falcke, Doeleman and other scientists from several continents formed the EHT collaboration. They ran their first Earth-spanning observation campaign during a two-week window in April 2017, looking at two

The first direct image of a black hole shows the void at the heart of the galaxy M87.

EHT COLLABORATION

black holes — Sagittarius A*, at the centre of the Milky Way, and the one in M87.

The raw data ran into petabytes. When the researchers first looked at them in mid-2018, they realized that they would be able to get a clean picture from M87. "We focused all our attention on M87 when we saw our first results, because we saw this is going to be awesome," says Falcke. Four separate teams started reconstructing an image without communicating with one another, to avoid bias. They all came to similar conclusions, so last November they began to write up their results.

SURPRISE AND RELIEF

The image unveiled on 10 April provides clear evidence of a photon ring around the black hole, says Andrea Ghez, an astronomer at the University of California, Los Angeles. "I was so delighted."

"It was a great sense of relief to see this, but also surprise," says Doeleman, adding that at this first attempt, he expected to see simply "a blob". "To see this ring is probably the best outcome that we could have had."

The shades of orange represent not colours, but the varying intensity of 1.3-millimetre radio waves emitted by plasma spiralling towards the black hole at nearly the speed of light.

The matter is seen orbiting clockwise, but its orbit is not exactly face on to Earth. As a consequence, the light the EHT sees is brighter on one side, where the matter is moving closer to the observer, than on the other, where it moves away, says Luciano Rezzolla, a theoretical astrophysicist at the Goethe University Frankfurt in Germany and a member of the EHT team.

The darkness of the shadow in the middle confirms general relativity's key prediction about black holes — the existence of the event horizon. So far, however, the image is not sharp enough to rule out all alternative theories of gravity, the authors wrote in their reports. Further studies could help researchers understand how the black hole produces gigantic jets of matter.

The team will now turn its attention to the Sagittarius A* data. Because this black hole is a mere one-thousandth the mass of the one in M87, matter orbited it many times in each observing session, producing a rapidly changing signal, Rezzolla says. That makes the data more complicated, but potentially richer.

The EHT collaboration plans to continue making observations of the two black holes once a year, starting in 2020. ■

DATA BOUNTY

Six puzzles the black-hole data can solve

Physicists can use the petabytes of data produced by the Event Horizon Telescope to answer long-standing questions about the general theory of relativity and more.

Three things physicists have confirmed

- The black hole's 'shadow' — the dark region at the centre of the photograph — is as dark as predicted by general relativity.
- The glowing 'photon ring' is brighter on one side than the other, showing that the black hole — or the matter orbiting it, or both — is rotating clockwise in the sky.
- The black hole's mass is 6.5 billion times that of the Sun, resolving a disparity between techniques for estimating mass.

Three things physicists can now measure

- Whether the photon ring is circular or squashed, as predicted for a rotating black hole. This would provide physicists with the speed of the black hole's spin.
- Whether, in the region of a black hole, there are slight deviations from general relativity. Physicists have already concluded that general relativity largely holds up.
- The polarization of the light received by the Event Horizon Telescope, which could help physicists to understand the mechanism that causes powerful 'jets' of matter to emanate from the black hole. **D.C. & N.G.**

Additional reporting by Emiliano Rodríguez Mega and Nisha Gaind.

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6. The Event Horizon Telescope Collaboration *et al.* *Astrophys. J.* **875**, L6 (2019).