

HOW TO BUILD A TIME MACHINE

It wouldn't be easy, but it might be possible **By Paul Davies**

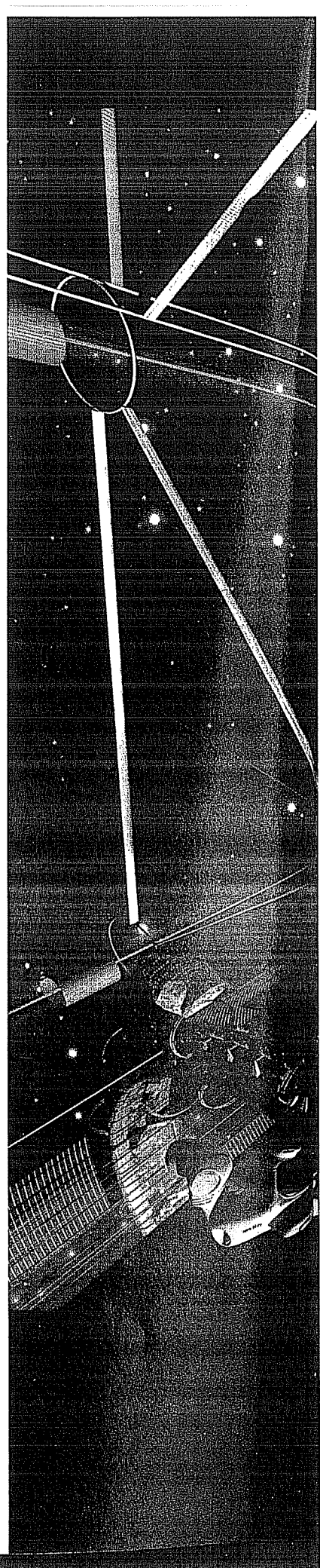
OVERVIEW

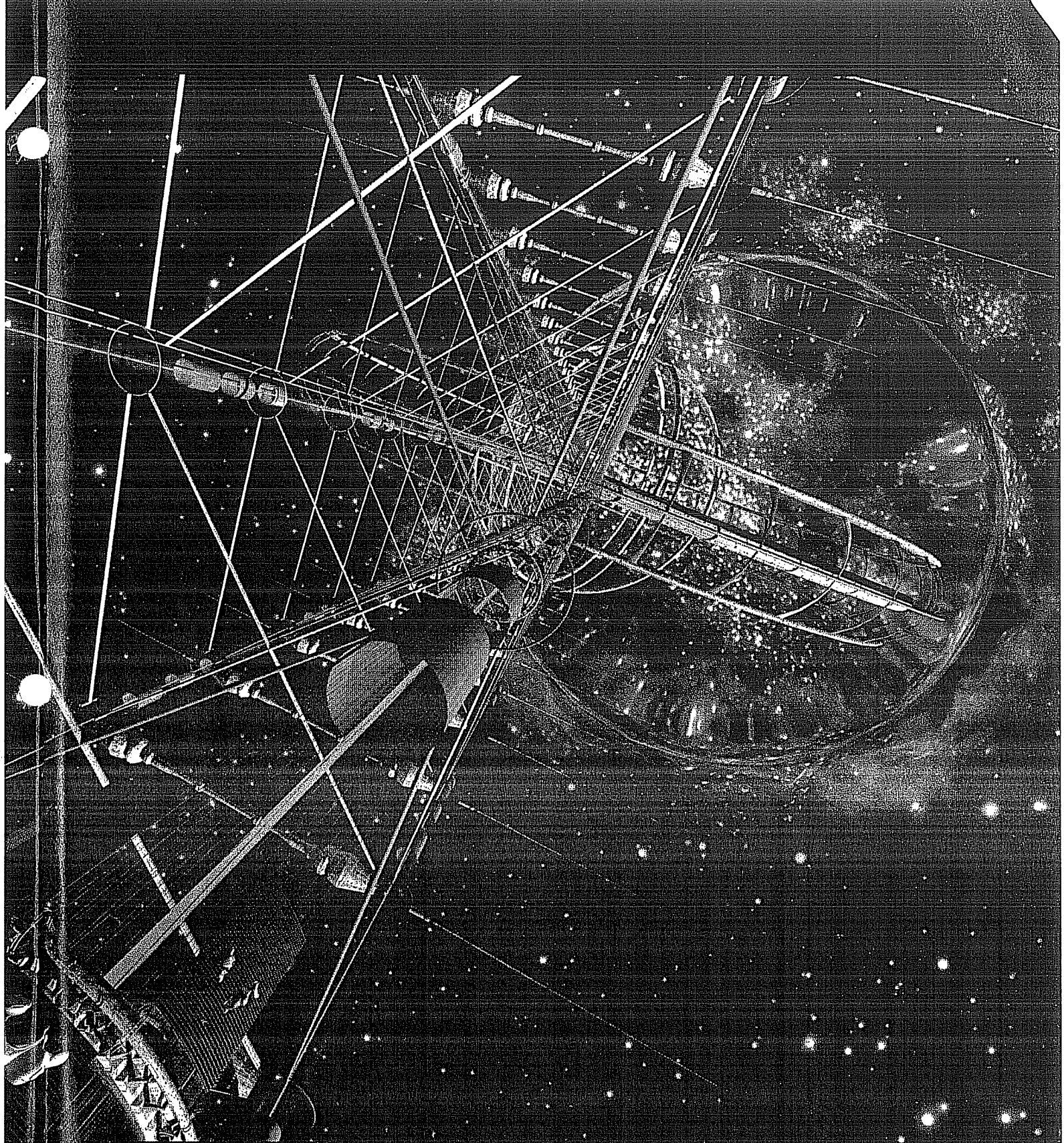
• Traveling forward in time is easy enough. If you move close to the speed of light or sit in a strong gravitational field, you experience time more slowly than other people do—another way of saying that you travel into their future.

• Traveling into the past is rather trickier. Relativity theory allows it in certain spacetime configurations: a rotating universe, a rotating cylinder and, most famously, a wormhole—a tunnel through space and time.

Time travel has been a popular science-fiction theme since H. G. Wells wrote his celebrated novel *The Time Machine* in 1895. But can it really be done? Is it possible to build a machine that would transport a human being into the past or future?

For decades, time travel lay beyond the fringe of respectable science. In recent years, however, the topic has become something of a cottage industry among theoretical physicists. The motivation has been partly recreational—time travel is fun to think about. But this research has a serious side, too. Understanding the relation between cause and effect is a key part of attempts to construct a unified theory of physics. If unrestricted time travel were possible, even in principle, the nature of such a unified theory could be drastically affected.





WORMHOLE GENERATOR/TOWING MACHINE is imagined by futurist artist Péter Bollinger. This painting depicts a gigantic space-based particle accelerator that is capable of creating, enlarging and moving wormholes for use as time machines.

Our best understanding of time comes from Einstein's theories of relativity. Prior to these theories, time was widely regarded as absolute and universal, the same for everyone no matter what their physical circumstances were. In his special theory of relativity, Einstein proposed that the measured interval between two events depends on how the observer is moving. Crucially, two observers who move differently will experience different durations between the same two events.

The effect is often described using the "twin paradox." Suppose that Sally and Sam are twins. Sally boards a rocket ship and travels at high speed to a nearby star, turns around and flies back to Earth, while Sam stays at home. For Sally the duration of the journey might be, say, one year, but when she returns and steps out of the spaceship, she finds that 10 years have elapsed on Earth. Her brother is now nine years older

in Earth's frame of reference they seem to take tens of thousands of years. If time dilation did not occur, those particles would never make it here.

Speed is one way to jump ahead in time. Gravity is another. In his general theory of relativity, Einstein predicted that gravity slows time. Clocks run a bit faster in the attic than in the basement, which is closer to the center of Earth and therefore deeper down in a gravitational field. Similarly, clocks run faster in space than on the ground. Once again the effect is minuscule, but it has been directly measured using accurate clocks. Indeed, these time-warping effects have to be taken into account in the Global Positioning System. If they weren't, sailors, taxi drivers and cruise missiles could find themselves many kilometers off course.

At the surface of a neutron star, gravity is so strong that

The wormhole was used as a fictional device by Carl Sagan in his novel *Contact*.

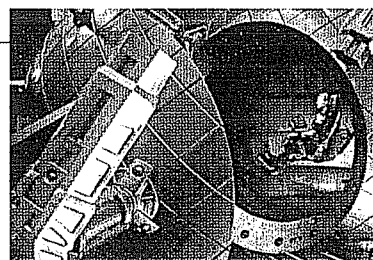
than she is. Sally and Sam are no longer the same age, despite the fact that they were born on the same day. This example illustrates a limited type of time travel. In effect, Sally has leaped nine years into Earth's future.

Jet Lag

THE EFFECT, KNOWN AS time dilation, occurs whenever two observers move relative to each other. In daily life we don't notice weird time warps, because the effect becomes dramatic only when the motion occurs at close to the speed of light. Even at aircraft speeds, the time dilation in a typical journey amounts to just a few nanoseconds—hardly an adventure of Wellsian proportions. Nevertheless, atomic clocks are accurate enough to record the shift and confirm that time really is stretched by motion. So travel into the future is a proved fact, even if it has so far been in rather unexciting amounts.

To observe really dramatic time warps, one has to look beyond the realm of ordinary experience. Subatomic particles can be propelled at nearly the speed of light in large accelerator machines. Some of these particles, such as muons, have a built-in clock because they decay with a definite half-life; in accordance with Einstein's theory, fast-moving muons inside accelerators are observed to decay in slow motion. Some cosmic rays also experience spectacular time warps. These particles move so close to the speed of light that, from their point of view, they cross the galaxy in minutes, even though

time is slowed by about 30 percent relative to Earth time. Viewed from such a star, events here would resemble a fast-forwarded video. A black hole represents the ultimate time warp; at the surface of the hole, time stands still relative to Earth. This means that if you fell into a black hole from nearby, in the brief interval it took you to reach the surface, all of eternity would pass by in the wider universe. The region within the black hole is therefore beyond the end of time, as far as the outside universe is concerned. If an astronaut could zoom very close to a black hole and return unscathed—admittedly a fanciful, not to mention foolhardy, prospect—he could leap far into the future.



My Head Is Spinning

SO FAR I HAVE DISCUSSED travel forward in time. What about going backward? This is much more problematic. In 1948 Kurt Gödel of the Institute for Advanced Study in Princeton, N.J., produced a solution of Einstein's gravitational field equations that described a rotating universe. In this universe, an astronaut could travel through space so as to reach his own past. This comes about because of the way gravity affects light. The rotation of the universe would drag light (and thus the causal relations between objects) around with it, enabling a material object to travel in a closed loop in space that is also a closed loop in time, without at any stage exceeding the speed of light in the immediate neighborhood of the particle. Gödel's solution was shrugged aside as a mathematical curiosity—after all, observations show no sign that the universe as a whole is spinning. His result served

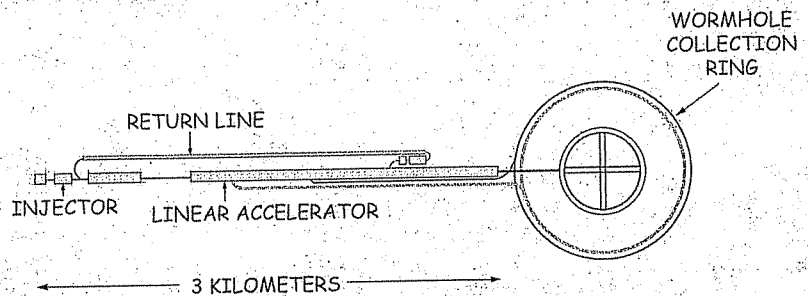
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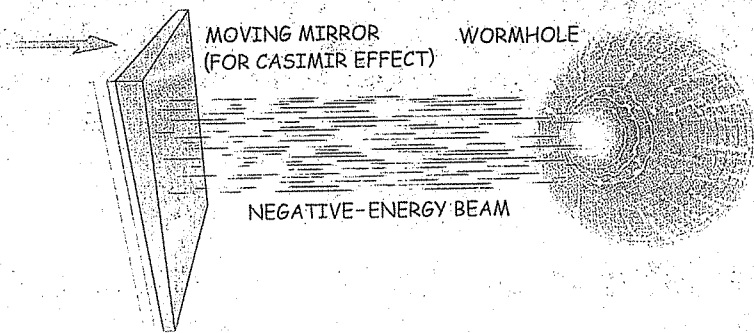
PETER BOLLINGER (preceding page); EVERETT COLLECTION (above)

A Wormhole Time Machine in Three Not So Easy Steps

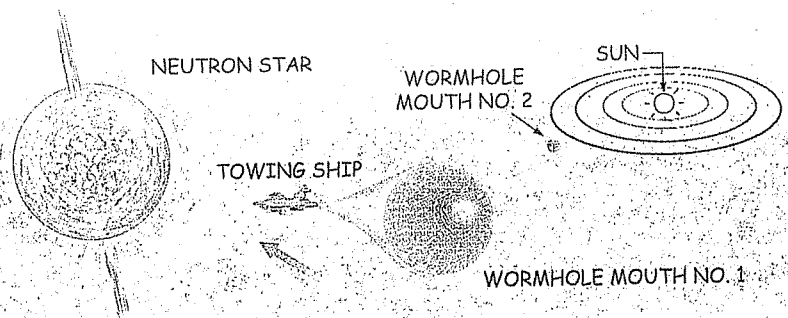
1 FIND OR BUILD A WORMHOLE—a tunnel connecting two different locations in space. Large wormholes might exist naturally in deep space, a relic of the big bang. Otherwise we would have to make do with subatomic wormholes, either natural ones (which are thought to be winking in and out of existence all around us) or artificial ones (produced by particle accelerators, as imagined here). These smaller wormholes would have to be enlarged to useful size, perhaps using energy fields like those that caused space to inflate shortly after the big bang.



2 STABILIZE THE WORMHOLE. An infusion of negative energy, produced by quantum means such as the so-called Casimir effect, would allow a signal or object to pass safely through the wormhole. Negative energy counteracts the tendency of the wormhole to pinch off into a point of infinite or near-infinite density. In other words, it prevents the wormhole from becoming a black hole.



3 TOW THE WORMHOLE. A spaceship, presumably of highly advanced technology, would separate the mouths of the wormhole. One mouth might be positioned near the surface of a neutron star, an extremely dense star with a strong gravitational field. The intense gravity causes time to pass more slowly. Because time passes more quickly at the other wormhole mouth, the two mouths become separated not only in space but also in time.



nonetheless to demonstrate that going back in time was not forbidden by the theory of relativity. Indeed, Einstein confessed that he was troubled by the thought that his theory might permit travel into the past under some circumstances.

Other scenarios have been found to permit travel into the past. For example, in 1974 Frank J. Tipler of Tulane University calculated that a massive, infinitely long cylinder spinning on its axis at near the speed of light could let astronauts visit their own past, again by dragging light around the cylinder into a loop. In 1991 J. Richard Gott of Princeton Uni-

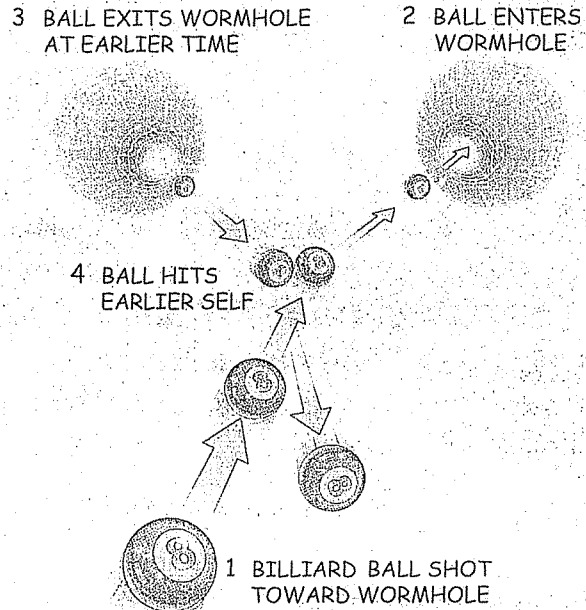
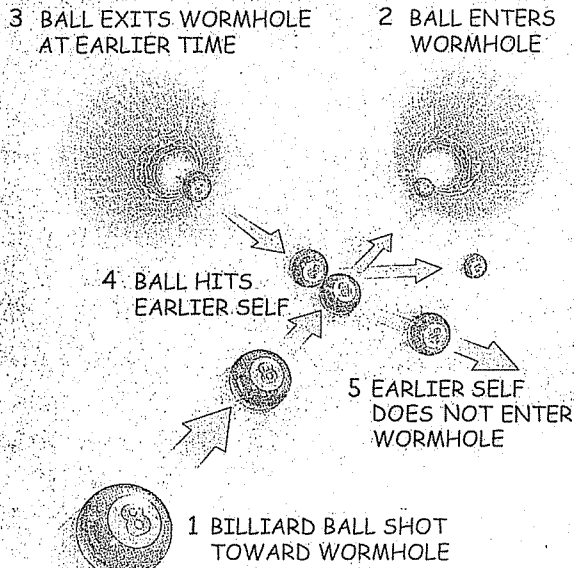
versity predicted that cosmic strings—structures that cosmologists think were created in the early stages of the big bang—could produce similar results. But in the mid-1980s the most realistic scenario for a time machine emerged, based on the concept of a wormhole.

In science fiction, wormholes are sometimes called star-gates; they offer a shortcut between two widely separated points in space. Jump through a hypothetical wormhole, and you might come out moments later on the other side of the galaxy. Wormholes naturally fit into the general theory of rel-

Mother of All Paradoxes

THE NOTORIOUS MOTHER PARADOX (sometimes formulated using other familial relationships) arises when people or objects can travel backward in time and alter the past. A simplified version involves billiard balls. A billiard ball passes through a wormhole time machine. Upon emerging, it hits its earlier self, thereby preventing it from ever entering the wormhole.

RESOLUTION OF THE PARADOX proceeds from a simple realization: the billiard ball cannot do something that is inconsistent with logic or with the laws of physics. It cannot pass through the wormhole in such a way that will prevent it from passing through the wormhole. But nothing stops it from passing through the wormhole in an infinity of other ways.



activity, whereby gravity warps not only time but also space. The theory allows the analogue of alternative road and tunnel routes connecting two points in space. Mathematicians refer to such a space as multiply connected. Just as a tunnel passing under a hill can be shorter than the surface street, a wormhole may be shorter than the usual route through ordinary space.

The wormhole was used as a fictional device by Carl Sagan in his 1985 novel *Contact*. Prompted by Sagan, Kip S.

Thorne and his co-workers at the California Institute of Technology set out to find whether wormholes were consistent with known physics. Their starting point was that a wormhole would resemble a black hole in being an object with fearsome gravity. But unlike a black hole, which offers a one-way journey to nowhere, a wormhole would have an exit as well as an entrance.

In the Loop

FOR THE WORMHOLE to be traversable, it must contain what Thorne termed exotic matter. In effect, this is something that will generate antigravity to combat the natural tendency of a massive system to implode into a black hole under its intense weight. Antigravity, or gravitational repulsion, can be generated by negative energy or pressure. Negative-energy states are known to exist in certain quantum systems, which suggests that Thorne's exotic matter is not ruled out by the laws of physics, although it is unclear whether enough anti-gravitating stuff can be assembled to stabilize a wormhole [see "Negative Energy, Wormholes and Warp Drive," by Lawrence H. Ford and Thomas A. Roman; *SCIENTIFIC AMERICAN*, January 2000].

Soon Thorne and his colleagues realized that if a stable

EXISTING FORMS OF FORWARD TIME TRAVEL

SYSTEM	SPECIFICATIONS	CUMULATIVE TIME LAG
Airline flight	920 km per hour for eight hours	10 nanoseconds (relative to inertial reference frame)
Nuclear submarine tour	300 meters' depth for six months	500 nanoseconds (relative to sea level)
Cosmic-ray neutron	10^{18} electron volts	Mean life stretched from 15 minutes to 30,000 years
Neutron star	Redshift 0.2	Time intervals expand 20 percent (relative to deep space)

PHILIP HOWE

PETER BOLLINGER

wormhole could be created, then it could readily be turned into a time machine. An astronaut who passed through one might come out not only somewhere else in the universe but somewhere else, too—in either the future or the past.

To adapt the wormhole for time travel, one of its mouths could be towed to a neutron star and placed close to its surface. The gravity of the star would slow time near that wormhole mouth, so that a time difference between the ends of the wormhole would gradually accumulate. If both mouths were then parked at a convenient place in space, this time difference would remain frozen in.

Suppose the difference were 10 years. An astronaut passing through the wormhole in one direction would jump 10 years into the future, whereas an astronaut passing in the other direction would jump 10 years into the past. By returning to his starting point at high speed across ordinary space, the second astronaut might get back home before he left. In other words, a closed loop in space could become a loop in time as well. The one restriction is that the astronaut could not return to a time before the wormhole was first built.

Even if time travel isn't strictly paradoxical, it is certainly weird. Consider the time traveler who leaps ahead a year and reads about a new mathematical theorem in a future edition of *Scientific American*. He notes the details, returns to his own time and teaches the theorem to a student, who then writes it up for *Scientific American*. The article is, of course, the very one that the time traveler read. The question then arises: Where did the information about the theorem come from? Not from the time traveler, because he read it, but not from the student either, who learned it from the time traveler. The information seemingly came into existence from nowhere, reasonlessly.

The bizarre consequences of time travel have led some scientists to reject the notion outright. Stephen W. Hawking of the University of Cambridge has proposed a "chronology protection conjecture," which would outlaw causal loops. Because the theory of relativity is known to permit causal loops, chronology protection would require some other factor to intercede to prevent travel into the past. What might this factor be? One suggestion is that quantum processes will come

It is conceivable that the next generation of particle accelerators will be able to create subatomic wormholes.

A formidable problem that stands in the way of making a wormhole time machine is the creation of the wormhole in the first place. Possibly space is threaded with such structures naturally—relics of the big bang. If so, a supercivilization might commandeer one. Alternatively, wormholes might naturally come into existence on tiny scales, the so-called Planck length, about 20 factors of 10 as small as an atomic nucleus. In principle, such a minute wormhole could be stabilized by a pulse of energy and then somehow inflated to usable dimensions.

Censored!

ASSUMING THAT the engineering problems could be overcome, the production of a time machine could open up a Pandora's box of causal paradoxes. Consider, for example, the time traveler who visits the past and murders his mother when she was a young girl. How do we make sense of this? If the girl dies, she cannot become the time traveler's mother. But if the time traveler was never born, he could not go back and murder his mother.

Paradoxes of this kind arise when the time traveler tries to change the past, which is obviously impossible. But that does not prevent someone from being a part of the past. Suppose the time traveler goes back and rescues a young girl from murder, and this girl grows up to become his mother. The causal loop is now self-consistent and no longer paradoxical. Causal consistency might impose restrictions on what a time traveler is able to do, but it does not rule out time travel per se.

to the rescue. The existence of a time machine would allow particles to loop into their own past. Calculations hint that the ensuing disturbance would become self-reinforcing, creating a runaway surge of energy that would wreck the wormhole.

Chronology protection is still just a conjecture, so time travel remains a possibility. A final resolution of the matter may have to await the successful union of quantum mechanics and gravitation, perhaps through a theory such as string theory or its extension, so-called M-theory. It is even conceivable that the next generation of particle accelerators will be able to create subatomic wormholes that survive long enough for nearby particles to execute fleeting causal loops. This would be a far cry from Wells's vision of a time machine, but it would forever change our picture of physical reality. ■



MORE TO EXPLORE

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- The Quantum Physics of Time Travel.** David Deutsch and Michael Lockwood in *Scientific American*, Vol. 270, No. 3, pages 68–74; March 1994.
- Black Holes and Time Warps: Einstein's Outrageous Legacy.** Kip S. Thorne. W. W. Norton, 1994.
- Time Travel in Einstein's Universe: The Physical Possibilities of Travel through Time.** J. Richard Gott III. Houghton Mifflin, 2001.
- How to Build a Time Machine.** Paul Davies. Viking, 2002.