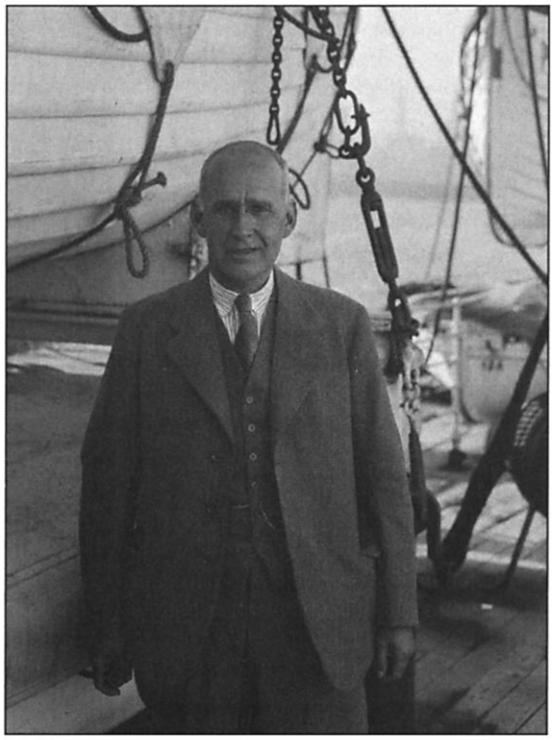
The Intelligent Noncosmologist's Guide to Spacetime

Since Einstein unleashed it on a bemused world, physicists have known that the stuff that shapes our universe is real, earnest, and increasingly useful. This pocket history explains how it came to be an indispensable part of their intellectual toolbox, and an asset to yours

The reality of spacetime first came crashing home on a little island near the coast of West Africa. On 29 May 1919, during a brief lull in a rainstorm on the island of Principe, Sir Arthur Eddington snapped 16 photographs of a solar eclipse. Those photographs changed our view of space and time. On them, Eddington saw a handful of stars that were in the wrong place.

"One thing is certain and the rest debate/Light rays, when near the Sun, do not go straight," Eddington exulted upon his return to England. Just as Albert Einstein had predicted, the sun's gravitational pull had subtly warped the fabric of space and time. Light that passes near the sun is bent, making stars near the sun's edge appear in the wrong positions. Eddington's photos proved that Einstein's bizarre theory about the fabric of space and time was more than mere fantasy. It was a hard reality.

More than 80 years later, the strange fabric that makes up our universe is more important than ever. Scientists have been devising test after test in attempts to trip up Einstein's description of the nature of space and time, and so far, all have confirmed the strange picture. The fabric of spacetime is real, and scientists can see it ripple and twist. Those undulations contain secrets of the birth and nature of the universe.



Far-seeing. Arthur Eddington won converts to Einstein's ideas with his photographs of distorted starlight.

Rubber sheets

The story of spacetime began in earnest in 1915, when Einstein formulated his general theory of relativity. The equations of general relativity liken space and time to a flexible fabric, something like a rubber sheet. One set of tools that mathematicians use to describe curving and stretchy objects constitutes a field of study called "differential geometry." Differential geometry allows mathematicians to probe curves and surfaces in space, and to define quantities such as "curvature" and "torsion" that describe their properties. And although a rubber-sheet spacetime seems like an artificial construct, it is a very natural and powerful idea when you have the tools to deal with it.

Why space and time, rather than just space? Einstein realized that motion in the everyday three dimensions of space (up-down, left-right, and back-front) also affects motion through the fourth dimension, time. For instance, if you move very, very fast in space, your wristwatch will tick very, very slowly in relation to your clock back on Earth. Although space and time have slightly different mathematical properties (our four-dimensional universe has three "spacelike" dimensions and one "timelike" one), they are inseparable. Change your motion through space and you automatically affect your motion through time, and vice versa. So in a mathematical sense, time and space are woven together into a single four-dimensional object.

The key equation of general relativity defines the relation between the curvature of spacetime and the energy and matter that are sitting on the sheet. And although it might seem odd to discuss the shape of the fabric of the universe—and a four-dimensional fabric, at that—it makes perfect sense to mathematicians and physicists. It also cleared up some long-standing mysteries.

For one, it explained where gravity comes from. A heavy object, such as our sun, distorts that spacetime fabric, bending it slightly, like a bowling ball on a mattress. If you place a marble on the mattress, it will fall toward the bowling ball, because of the curvature of the mattress. Likewise, if you place an asteroid near the sun, it will fall toward the sun, because the curvature of spacetime forces it to move in that direction. Shortly after Einstein unveiled it, scientists realized that this gravity-as-curvature-of-spacetime theory explained a mysterious anomaly in the orbit of Mercury. Newton's laws were unable to explain why the small planet's orbit shifted so quickly, and scientists had long been stumped for an explanation. Einstein's spacetime equations, however, diverge from Newton's in regions of strongly curved spacetime, such as those near a heavy body like the sun. That slight discrepancy perfectly explained Mercury's mercurial behavior.

A handful of scientists, including Eddington, quickly took notice of the new theory and tried to figure out a way to test its consequences. The problem was that, in our solar system, Einstein obviously differed from Newton only very close to our sun—and the sun is so bright that it is hard to observe anything close by. Hence the need to wait for a solar eclipse.

In 1919, Eddington's celebrated expedition to Principe was the first test of the concept of spacetime. Because our sun bends spacetime and light follows the contours of that fabric, the theory of relativity predicts that the sun must bend light that passes near it, something like a lens. A star whose light passes close to the sun, deep into the dimple that the sun makes in the rubber sheet, should appear in the wrong place. Its apparent position in the sky should be somewhat altered by the gravitational pull of the sun.

This is, of course, precisely what Eddington saw. As the solar eclipse blotted out the sun, the newly visible stars were not in their proper places. Eddington and his team had

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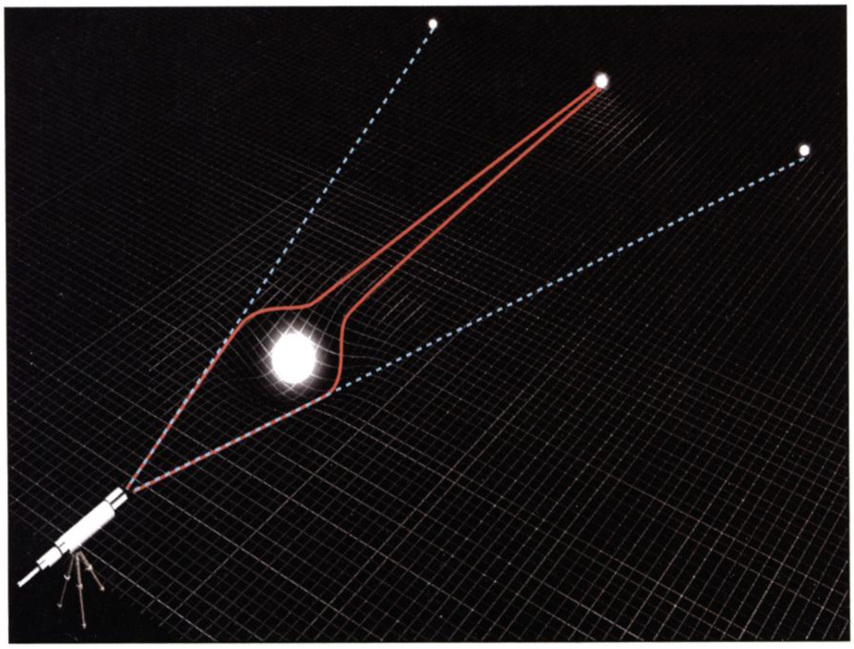
seen the curvature of spacetime: They had spotted a "gravitational lens." Einstein was right. Spacetime was real.



Cosmic mirage. By warping the spacetime around it, a massive object can cause light from a more distant star or galaxy to take different routes to Earth. Such "gravitational lensing" can split a single object into two or more images.

Wrinkles in time and Einstein in drag

Six decades passed before astronomers spotted another of gravitational lensing's peculiar incarnations. If you have an enormous amount of matter, such as a galaxy cluster, and a distant, bright object is in the right place behind it, astronomers see double. Thanks to the bending effect of the matter in the lens, light from the background object takes several curved paths to Earth. As a result, astronomers see multiple images for a single object (see figure above). In 1979, astronomer Dennis Walsh and his colleagues spotted the first of these cosmic clones: two images of the same bright quasar in the heavens.

Meanwhile, scientists were studying another consequence of a spacetime fabric: gravitational waves. Gravitational waves are a natural offshoot of the rubber-sheet construction of general relativity. Just as a massive object sitting on the fabric of spacetime creates a dimple, so moving or changing objects, under certain conditions, create wrinkles in the fabric. Those wrinkles, tiny distortions in spacetime, zoom away at the speed of light. Because these gravitational waves carry energy, anything emitting them will lose a tiny bit of its speed.

The first sign of gravitational waves came from just such an energy loss. Jocelyn Bell, a graduate student at Cambridge University, set the stage for the discovery in 1967, when she found an object that blinked on and off in the sky, emitting incredibly regular pulses of radio waves. Soon thereafter, scientists spotted several similar objects in different regions of the sky and ruled out an artificial origin. Bell had seen the first pulsar, a spinning, burned-out husk of a star that emits a powerful beam of radiation. In 1974, Bell's adviser, Anthony Hewish, won the Nobel Prize for the discovery.

Barely a month before Hewish got the call from Stockholm, Joseph Taylor, an astronomer at Princeton University, and his graduate student, Russell Hulse, discovered a pulsar that was different from all the others that had been found. Its bursts seemed to be less regular, speeding up and slowing down rather than ticking away with unchanging tempo. Hulse and Taylor realized that they were seeing a binary pulsar—a pulsar orbiting an unseen companion. As the pulsar sweeps out its orbit in space, it zooms toward and away from Earth, making the pulses seem to speed up and slow down, even though the star itself spins with clocklike precision. The pulsar, ticking away like an enormous metronome as it orbited its companion, gave scientists a way to test this prediction for the first time.

As the pulsar and its unseen companion dance around each other, they must wrinkle the fabric of spacetime—they must emit gravitational waves. Those gravitational waves carry away some of the stars' energy, slowing them down and causing them to fall inward. Their orbits get shorter and shorter as they get closer and closer together. In 1978, Taylor and his colleagues showed that this was precisely what the binary pulsar was doing. Every year, the pair's orbit took 75 milliseconds less than it did the previous year. The tiny decrease marked the first evidence for gravitational waves. In 1993, Taylor and Hulse won the Nobel Prize for the discovery.

Another hard-to-measure consequence of spacetime is "frame dragging." In 1918, physicists Joseph Lense and Hans Thirring realized that spinning massive objects twist spacetime just as colliding massive objects wrinkle it. Astronomers working in a twisting spacetime will have their perceptions, their measurements of the universe, slightly skewed. As a result, a celestial "compass" that provided a perfect measurement of an observer's orientation in relation to distant galaxies would fail if the observer were in a region of twisting spacetime. The compass would seem to slip. If it started out pointing at the center of the Milky Way, it would soon wind up pointing in a different direction.

Indeed, scientists hope to see evidence of frame dragging, also known as the Lense-Thirring effect, by detecting the influence spinning bodies have on gyroscopes—the best approximation we have of a celestial compass. Gyroscopes tend to maintain their orientation, unless twisted spacetime makes them change direction.

In 1997, two teams of scientists announced that they had seen the Lense-Thirring effect in action for the first time. Both teams used an orbiting x-ray observatory to chart the behavior of disks of hot gas around heavy spinning stars. One team, led by Wei Cui, then at the Massachusetts Institute of Technology, looked at spinning black holes, and the other, led by Luigi Stella of the Astronomical Observatory of Rome, observed spinning neutron stars. Both saw the orientations of the spinning accretion disks

Matter matters. "Wheel rim" distortions of some galaxies in this Hubble Space Telescope image of cluster Abell 2218 show the influence of unseen mass closer to Earth.

CREDITS: (TOP TO BOTTOM) ILLUSTRATION BY C. SLAYDEN; NASA/ESA/R. ELLIS (CALTECH) AND J. KNEIB (OBSERVATOIRE MIDI-PYRENEES)

A Foamy Road to Ultimate Reality

What is the fabric of spacetime made of? We know spacetime can ripple and curve and twist, but what does its fabric look like on very small scales? Nobody knows for sure, but when physicists find out, it may drastically alter our view of the universe—and of space and time.

"One thing we know absolutely for sure is that spacetime does not have a precise meaning at very short distance scales," says Harvard University physicist Andrew Strominger. The problem is that on small scales the fabric of spacetime must be subject to one of the key properties of quantum objects: the Heisenberg Uncertainty Principle, which states that a particle's momentum and position can't both be precisely defined at the same time. A direct consequence of this principle is that the universe is seething with particles and energy—a ubiquitous "quantum foam" that suffuses the cosmos, even in the deepest vacuum.

On smaller and smaller scales, the fabric of spacetime fluctuates with energy more and more dramatically. When you look at the fabric below a certain scale known as the "Planck length," the equations of general relativity can no longer describe the fabric. "Spacetime goes haywire," Strominger says, noting that scientists need to go beyond the theory of general relativity to describe the structure of the fabric itself. "The only real theory we have to discuss things is string theory."

String theory—and its generalization, M-theory—replaces pointlike particles such as electrons with higher dimensional objects, such as strings and membranes. That theoretical shift changes the way objects look on the very smallest scales and gets rid of some troubling problems that make general relativity's equations break down there. It also makes the string theorist's portraits of spacetime look very different from the traditional smooth fabric. "In some examples, if you go to tiny distances, it has a grainy structure of a rather subtle sort," says physicist Nima Arkani-Hamed, also at Harvard. "It's not like a picture where there's a little lattice, but there's some sense in which there's discreteness on tiny scales."

In a sense, spacetime doesn't have any meaning at sizes below the Planck length. If scientists managed somehow to build a powerful enough particle accelerator to see the structure of spacetime below the Planck length, they would hit a brick wall. "When you start to probe spacetime on shorter and shorter distances, you are stymied," says Arkani-Hamed. "You'd start creating little black holes." Those black holes would decay, releasing a shower of particles, but once you start making black holes, you get no further information about the structure of spacetime.

Despite this depressing scenario, theorists are trying to figure out what the nature of spacetime might be. "We haven't put it all together into a unified picture of what happens to spacetime in general," says Strominger. "But there are very interesting statements one can make about the nature of spacetime at short distances."

String theorists don't know what rules apply to our universe, but they are able to analyze how the quantum foam and the fabric of the universe behave under certain situations. In one of these scenarios, says Arkani-Hamed, the concept of space disappears on small-length scales. "When you get to distances shorter than the Planck length, really, fundamentally, there's no space at all," he says. It's a mind-boggling idea, but in a sense, the idea of space can become redundant; it emerges from more fundamental properties of objects. "Space itself is created out of the interactions of particles."

Scientists have cooked up many such possibilities, each of which might or might not apply to our universe. Still, string theorists hope that they will eventually understand which equations truly describe the fabric of spacetime. "Everything is pointing to the fact that spacetime is only an approximate concept," says Strominger. "It's not the absolutely ultimate concept, and we're desperately struggling to find out what the right language to describe the universe is."

–C.S.

wobble. The enormous gyroscopes were rotating relative to the rest of the universe, just as the equations of spacetime predict.

Although the evidence is not yet conclusive, scientists hope to see the frame-dragging effect directly, thanks to a half-billion-dollar satellite, Gravity Probe B, which is slated to be launched early in 2003. Essentially a fancy gyroscope, the probe will try to sense the subtle frame dragging caused by Earth's spin.

Scientists also hope to see gravitational waves directly, using a nearly $400 million experiment known as the Laser Interferometer Gravitational Wave Observatory (LIGO). LIGO's two facilities in Washington and Louisiana house sensitive devices meant to detect the subtle squish and stretch of spacetime caused by a passing gravitational wave. The facilities are almost fully operational; scientists are busy shaking down the instruments, trying to isolate the sources of noise. Any day now, they will be taking their first scientific data.

Nobody knows quite what LIGO will see—possibly nothing at all. The waves it is most likely to spot come from spiraling and colliding neutron stars and black holes, and scientists don't know precisely how much gravitational radiation from these sorts of events is rattling around the universe. But if LIGO does see the signature of a gravitational wave, it will be a tremendous accomplishment; it will give scientists their first direct view of a moving distortion in spacetime. More important, gravitational radiation will become a tool for understanding the black holes and neutron stars in our universe. Charting the heavens with gravity waves as well as light waves may reveal secrets of the universe that traditional astronomy has failed to uncover.

Spacetime as a tool

Even without gravitational waves, the subtle curvature of spacetime near enormous objects is helping scientists tackle one of their most pressing astrophysical questions: the nature of dark matter. For the past decade, one incarnation of the warping of spacetime, known as "microlensing," has been revealing hunks of matter called MACHOs: massive, compact halo objects. Nobody is quite sure what these might be; they could be burned-out stars or

ILLUSTRATION BY TIM SMITH

brown dwarfs, stars too light to ignite their fusion engines. But whatever they are, they have mass, and therefore they warp the fabric of spacetime. As a MACHO passes in front of a background star, the gravitational pull of the MACHO warps the fabric of spacetime and bends the light so that more of it is focused on Earth. As Earth receives more and more light from the star, the star appears to brighten, and as the MACHO moves away over the course of a few weeks, the star dims, once again, to its original luminosity.

An international team of astronomers and astrophysicists, known as the MACHO project, has been using telescopes in Australia and the United States to look for these signature flickers in background stars. (There are also several competing groups, such as the aptly named OGLE collaboration.) Since the MACHO project began in 1993, it has spotted hundreds of these microlensing events; nowadays, astronomers spot about one a week. The flood of data is allowing astronomers to chart where the dark matter resides in our galaxy—and may allow them to figure out what it's made of. Because black holes distort spacetime in a slightly different manner from brown dwarfs, astronomers might be able to tell what sort of massive bodies are floating about in the halo.

Curvature of spacetime can also reveal the presence of invisible matter in galaxies and galaxy clusters by measuring how dramatically their mass reroutes the light from objects behind them. The more dramatic the distortion, the more matter there is and the more tightly packed it is. In mid-2001, scientists at Bell Labs used such large-scale lensing to discover a previously unknown "dark" cluster of galaxies 3.5 billion light-years away (*Science*, 17 August 2001, p. 1234). But the shape of spacetime holds an even more exciting story than the birth of black holes or the secret of dark matter: It tells us about the nature of the cosmos.

The fabric of spacetime can have a curvature locally, like the distortions caused by the sun or by passing gravitational waves, or "globally," a curvature for the entire universe. It's somewhat like the situation on our own planet: Locally, Earth's surface has peaks and valleys, rolling hills and crevasses, and little lumps that affect a small area. But zoom out far enough, and you see that Earth is a sphere, even though the curvature is all but imperceptible across small distances.

It's the same with the universe as a whole. Locally, spacetime can be flat or rippled; it can even gape with immense, seemingly bottomless pits. The universe as a whole, however, also has a shape. It might be flat, or it might have "positive curvature" like a ball, or "negative curvature" like a saddle. All of these shapes are in four dimensions, of course, so they're very difficult to visualize, even with mathematical training. Nonetheless, the three-dimensional versions—a plane, a sphere, or an enormous saddle—are reasonable approximations of our 4D universe.

In the past 2 years, scientists have measured the shape of the universe by looking at features in the cosmic background radiation, the ubiquitous hiss of microwave energy left over from a time shortly after the big bang. According to theory, there are spots in that radiation, and the spots have to be a certain size. By measuring the apparent size of those spots in the sky, cosmologists could figure out the shape of spacetime.

If spacetime were flat, two parallel light rays would stay the same distance apart as they approach us, making distant features look precisely as large as they should. But on a surface with "positive" curvature, approaching rays would move farther apart, making distant objects look bigger; on a surface with "negative" curvature, the beams would get closer together, making distant objects look smaller (see figure below). In 2000, a balloon observatory known as BOOMERANG measured the size of those spots for the first time—and they were precisely as large as expected (*Science*, 28 April 2000, p. 595). The data were powerful evidence that the universe has no curvature. A year later, another set of experiments, DASI and Maxima, confirmed BOOMERANG's discovery (*Science*, 4 May 2001, p. 823). Physicists are virtually unanimous: The world is round, but the universe seems to be flat.

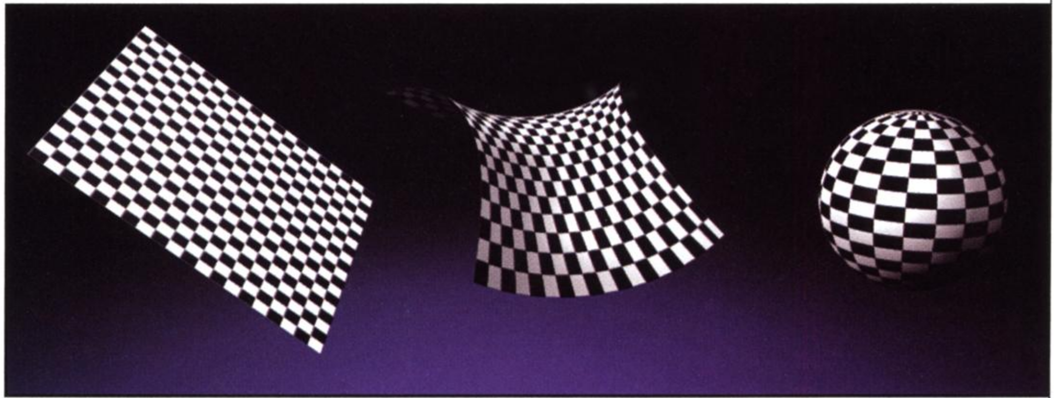
The shape of the universe tells scientists about the mass and energy that sit upon the fabric of spacetime. When astronomers and astrophysicists totaled up the amount of matter in the universe, they discovered that it is only about 35% of what is needed to flatten out spacetime; judging by appearances, the universe ought to be saddle shaped. So cosmologists have concluded that there must be some other energy out there, some other "stuff" that flattens out the fabric of space and time. This is the mysterious "dark energy" that makes the universe expand ever faster and that has become one of the most profound mysteries in modern astrophysics.

If there's a mystery more profound than the nature of dark energy, it has to be the physics that governed the beginning of the universe. Shortly after the big bang, the fabric of space was rippling with gravitational radiation. Scientists hope that by the end of the decade they will be able to see the remnants of those wrinkles.

The peculiar squash-and-stretch action of a gravitational wave affects the polarization of light waves—including those that make up the cosmic microwave background. The signature of ancient gravitational waves in the cosmic microwave background is a spiral quality that mathematicians call "curl." If one drew a map of the polarization of the cosmic background radiation, this curl-type component would look something like little hurricanes. The swirls are an artifact of the forces that brought our universe into being. They would contain the first bonanza of information about an era that had been totally inaccessible.

Several groups of scientists—including the BOOMERANG and DASI teams—are racing to detect polarization in the cosmic background radiation, but detecting the echoes of the ripples in ancient spacetime is probably beyond the reach of these experiments. We will have to wait until the Planck satellite, due to be launched in 2007, or another future experiment before scientists first see the subtle signature of the warps of ancient spacetime.

But when they see that signature, scientists will begin to see the marks of creation woven within the weft of the four-dimensional fabric of space and time. —CHARLES SEIFE



Which universe? Depending on how spacetime curves on a large scale, light rays crossing the universe might remain parallel, converge, or drift apart.

ILLUSTRATION BY C. SLAYDEN