NEWS

Special Relativity Reconsidered

Einstein's special theory of relativity reaches into every corner of modern physics. So why are so many trying so hard to prove it wrong?

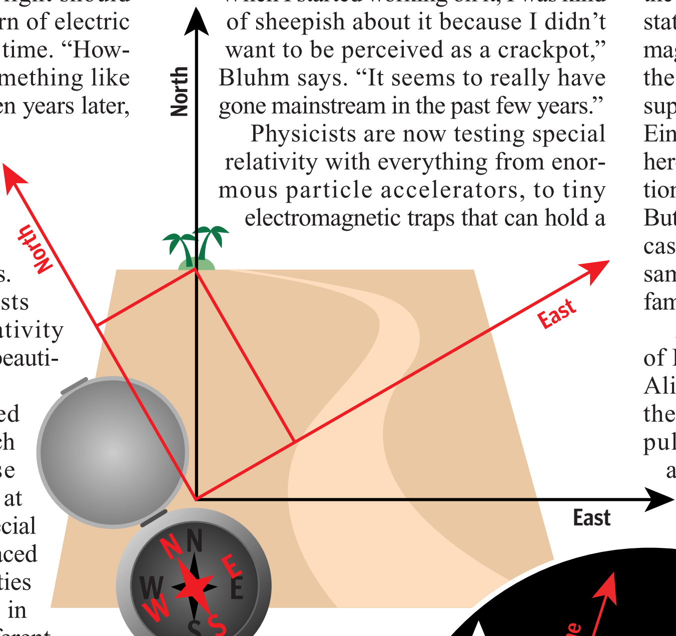
At an age when most boys would rather chase girls, Albert Einstein daydreamed of chasing light. When he was about 16 years old, Einstein later recalled, he realized that if he ran fast enough to catch up to it, light should appear to him as a wavy pattern of electric and magnetic fields frozen in time. "However," Einstein observed, "something like that does not seem to exist!" Ten years later, that insight blossomed into the special theory of relativity, which forbade catching light, overturned ancient conceptions of time and space, and laid the cornerstone for modern physics. Now, however, some physicists wonder whether special relativity might be subtly—and perhaps beautifully—wrong.

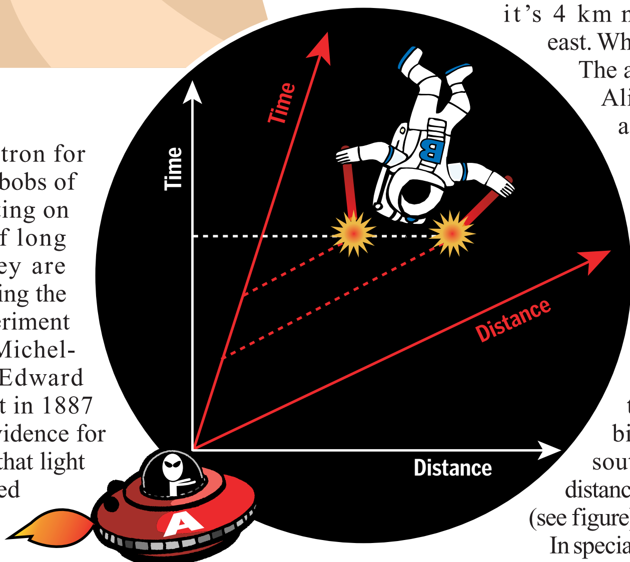
In 1905, physicists believed space was a grand stage on which the drama of the universe unfolded and time ticked away at the same rate for all actors. Special relativity denied all that. It replaced space and time as distinct entities with a single "spacetime" that, in mind-bending ways, looks different to observers moving relative to each other. But the theory's implications reach far beyond questions of when and where. Combined with quantum mechanics, it helps explain the stability of matter and even requires the existence of antimatter, says Steven Weinberg, a theoretical physicist at the University of Texas, Austin. "That's the only way nature can be if you're going to satisfy the requirements of both relativity and quantum mechanics," Weinberg says.

Yet a growing number of physicists are entertaining the possibility that special relativity is not quite correct. That may sound perverse, but researchers have good reason to hope Einstein's theory isn't the final word: Any deviation from special relativity could point physicists toward an elusive goal, a quantum theory of gravity. Candidate theories can be tested directly only with particle collisions a million, billion times more energetic than any produced with a particle accelerator. On the other hand, testing special relativity provides a far more practical, albeit indirect, way of probing quantum gravity, says V. Alan Kostelecký, a theorist at Indian University, Bloomington.

Only a decade ago, questioning special relativity would have struck many as heretical, says Robert Bluhm, a theoretical physicist at Colby College in Waterville, Maine. "When I started working on it, I was kind of sheepish about it because I didn't want to be perceived as a crackpot," Bluhm says. "It seems to really have gone mainstream in the past few years."

Physicists are now testing special relativity with everything from enormous particle accelerators, to tiny electromagnetic traps that can hold a single electron for months, to bobs of metal twisting on the ends of long fibers. They are even repeating the famed experiment by Albert Michelson and Edward Morley that in 1887 found no evidence for the "ether" that light was supposed to ripple through just as sound ripples through air. In spite of these efforts, special relativity remains inviolate—so far.





Unbearable coincidences

According to legend, Einstein invented special relativity to explain the Michelson-Morley experiment. In truth, he worried more about conceptual puzzles in the theory of electricity and magnetism, which had been hammered out in the 1860s by the Scottish physicist James Clerk Maxwell, says Michel Janssen, a historian of science at the University of Minnesota, Twin Cities.

Consider the simplest electrical generator—a loop of wire and a magnet moving toward each other at constant speed. Current will flow through the wire. According to Maxwell's theory, different mechanisms drive the current depending on whether the wire is stationary in the presupposed ether and the magnet is moving or the other way around. Yet the current is the same in either case. That supposed coincidence was too fantastic for Einstein. "The idea that we would be dealing here with two fundamentally different situations was unbearable to me," he later wrote. But Einstein found he could show that the two cases were different ways of looking at the same thing—if he abandoned the ether and familiar notions of space and time.

A simple analogy captures the essence of Einstein's insight. Imagine two explorers, Alice and Bob, lost in a vast desert. From the top of a dune they spot an oasis. Alice pulls out her compass and range finder and determines that the oasis is 5 kilometers due north. Bob takes his own measurements and finds that it's 4 km north and 3 km east. What's gone wrong? The answer is simple: Alice and Bob disagree because their compasses don't line up. Each has a different notion of north, so what Alice takes to be a purely north-south distance, Bob takes to be a combination of north-south and east-west distances, and vice versa (see figure).

In special relativity, traveling at a constant speed relative to another observer mixes time and space in much the same way. For example, imagine that instead of explorers, Alice and Bob are astronauts in deep space. Suppose, in a fit of foolishness, Bob holds up a firecracker in each of his outstretched hands. He sets the explosives off as Alice zooms past at half the speed of light. If Bob sees both firecrackers flash at the same time, Alice will see them flash at different times. So what Bob perceives as a purely spatial distance, Alice perceives as a spatial

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distance and a time interval. In essence, there is only one spacetime, which they perceive as different combinations of space and time.

In precisely the same way, in Einstein's analysis there is only one underlying "electromagnetic" field that requires no ether, and different observers slice it into different combinations of electric and magnetic fields. The underlying unity explains why the current in the simple generator is the same regardless of whether the magnet or the wire is moving. In fact, according to special relativity it's meaningless to say which is "really" moving.

Outgrowing Einstein

Einstein doggedly followed his theory to bizarre but unavoidable conclusions. A clock whizzing by at near light speed ticks slower than the watch on your wrist. A meter stick flying past looks shorter than one in your hands. Light travels at the same speed for all observers—so it cannot be caught.

But special relativity packs even more punch when combined with quantum mechanics to form "relativistic quantum field theory." That amalgam predicts the existence of antimatter and demands a kind of mirrorlike correspondence between matter and antimatter, which is known as CPT symmetry. It also forges a connection between how much particles spin like little tops and whether two or more of them can occupy the exact same quantum state. That "spin-statistics connection" explains why atoms and nuclei do not implode.

Antimatter must exist because quantum mechanics blurs notions of before and after, at least for particles, says the University of Texas's Weinberg. Suppose Alice throws an electron and Bob catches it. Observers moving at different speeds will disagree on how long it takes the electron to make the trip, but, sans quantum mechanics, all will agree that Alice throws it before Bob catches it. Mix in the uncertainty principle, however, and some observers will see Bob receive the electron before Alice tosses it, Weinberg says. "And the way that relativistic field theory gets around that difficulty is by reinterpreting it as Bob emits an antielectron that Alice receives," he says. However, the conceptual fix-up works only if the electron and antielectron have exactly the same mass and other properties—collectively, CPT symmetry.

The spin-statistics connection is less intuitive. All particles behave like little tops and can have only certain amounts of spin. For example, the photons that make up light have exactly one quantum of spin, whereas the electrons, protons, and neutrons that make up atoms have half a quantum. The spin-statistics connection says that no two identical particles can occupy the same quantum state if they have spin 1/2 (or 3/2, 5/2, etc.) That means the electrons in an atom cannot collapse into a tiny knot. Instead they stack into shell-like orbitals, and this arrangement keeps the atom stable. And it's a consequence of special relativity, says O. W. Greenberg, a theorist at the University of Maryland, College Park. "Violating the spin-statistics connection in a relativistic theory is, so far as we know, just impossible," Greenberg says.

Ironically, Einstein disdained the marriage of special relativity and quantum mechanics. "I know from experience how difficult it was to discuss quantum field theory with him," wrote his scientific biographer, Abraham Pais, who died in 2000. "Relativistic quantum field theory was repugnant to him." But Greenberg says we should not disparage Einstein because he didn't fully appreciate the implications of his own discovery: "It sort of outgrew Einstein."

As the world turns

Now, however, some physicists are hoping to reach beyond special relativity. Researchers generally agree that the ultimate theory of gravity cannot be a quantum field theory. Such theories assume that particles are infinitesimal points and spacetime is smooth. But according to the uncertainty principle, at minuscule scales spacetime ought to erupt into a chaotic froth that overwhelms any theory of point particles. On the other hand, calculations suggest that alternative theories—such as string theory, which assumes that every particle is really a tiny vibrating string—might not completely jibe with special relativity.

Unfortunately, sketchy quantum gravity theories cannot tell experimenters precisely what signs to look for, says Indiana University's Kostelecký. So over the last 15 years, he and his colleagues have taken another tack. They start with the relativistic quantum field theory that explains all the particles seen so far, the so-called Standard Model. They add to it myriad "background fields" that lace empty space. These resemble an electromagnetic field in that each points in some direction. But whereas electromagnetic fields arise from charges and currents, the background fields are woven into the vacuum. Known as the Standard Model Extension (SME), this catch-all theory clashes with special relativity because each background field provides a universal benchmark with which to determine whether an object is moving or not, or at least which direction it's going.

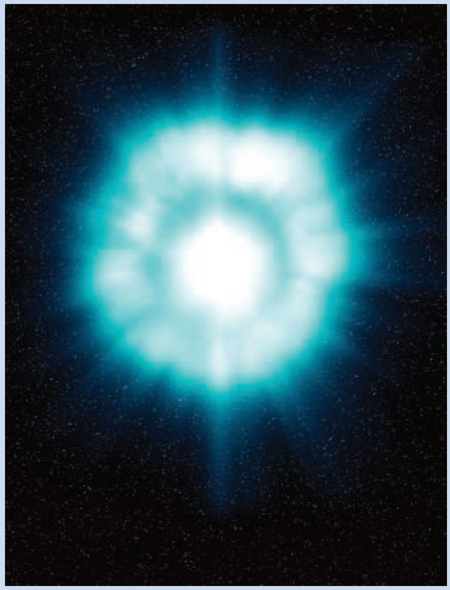
Experimenters are striving to glimpse the background fields, mainly by trying to detect Earth's motion through them. Because Earth spins, a lab will zoom through a background field at different angles at different times of

Doubly Special, Twice as Controversial

Quantum gravity may bend, not break, special relativity, some theorists say. Special relativity says that nothing can travel faster than light. Quantum gravity effects might also limit an individual particle's energy, says Giovanni Amelino-Camelia of the University of Rome "La Sapienza." That could lead to what he and others call "doubly special relativity." The embryonic theory has no background fields, and just as in ordinary special relativity, it's impossible to tell whether an object is moving relative to the vacuum. But the rules for adding up momentum and energy change, leading to potentially observable astronomical effects.

For example, doubly special relativity predicts that the speed of light could depend on its color and energy. Such an effect might be spotted by observing gargantuan stellar explosions known as gamma ray bursts, says Lee Smolin of the Perimeter Institute for Theoretical Physics in Waterloo, Canada. The gamma rays take billions of years to reach Earth, Smolin says, giving the faster ones time to pull measurably ahead of the slower ones.

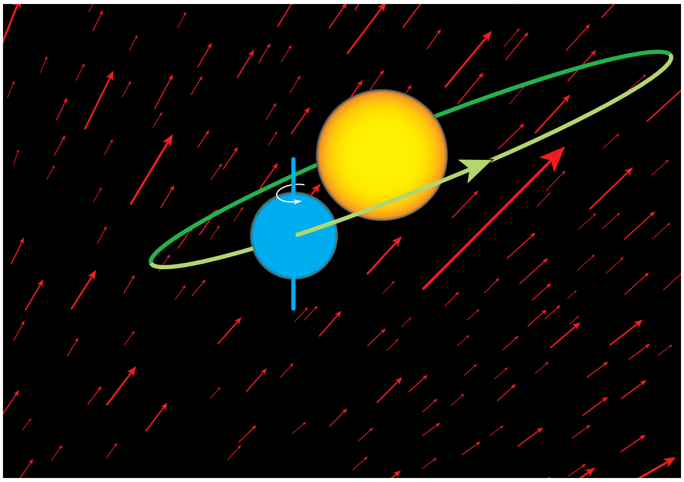
However, some theorists doubt that doubly special relativity can be made into a coherent theory. Amelino-Camelia says he sees no obvious reason why it can't. Still, he adds, "there are plenty of consistency checks to be made, and I offer no guarantees until they're done." –A.C.



Photon photo finish. Gamma rays from humongous stellar explosions may reveal hypothesized variations in the speed of light.

ILLUSTRATION: ESA/ECF

day. So if an experiment bolted to the floor can feel the field, its output should oscillate in sync with Earth's rotation. Researchers expect the effects to be tiny. Spotting them will require, for example, measuring the frequencies of microwaves to one part in 1000 billion or better. But "even though these effects are very small," Kostelecký says, "the current experimental capabilities are in the range that you would expect to see something" if the fields are there.



Feel the breeze. Experimenters hope to detect oscillating effects as Earth whizzes and spins through putative background fields.

SME has limitations. It doesn't explain how the background fields arise. And each type of particle may interact with a different set of fields, leaving experimenters with dozens of measurements to make. Nevertheless, SME tells researchers which experiments should be most sensitive and enables them to compare seemingly disparate efforts, which is why it has sparked much of the interest in testing special relativity, says Blayne Heckel, an experimental physicist at the University of Washington, Seattle. "Once you have this community out there that appreciates what you're doing," Heckel says, "you don't feel so bad measuring zero."

K^0 mesons and clocks in space

Heckel is hardly the only one to come up short in trying to prove Einstein wrong: Experimenters have found no evidence that special relativity isn't bang on the money. For decades particle physicists have tested CPT symmetry, which now can be analyzed in the context of SME, by comparing particles and antiparticles. Researchers working with the KTeV experiment at Fermi National Accelerator Laboratory in Batavia, Illinois, have shown that fleeting particles called K^0 (pronounced kay-zero) mesons have the same mass as their antiparticles to one part in a billion billion. By "weighing" individual particles in devices called Penning traps, researchers at the European particle physics laboratory, CERN, near Geneva, Switzerland, have shown that protons and antiprotons have the same mass to a part in 10 billion.

Others are probing for background fields by comparing extremely precise clocks. A background field may affect one clock differently from the other, in which case one will speed up and slow down relative to the other over the course of the day. In fact, the "clocks" can be two different frequencies of radiation emitted by the same atom. Using a device called a maser, Ronald Walsworth of the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts, and colleagues compared two frequencies emitted by hydrogen atoms, which allowed them to probe for fields that might affect the lone proton at the center of the hydrogen atom. No sign of the background fields emerged.

Some have resorted to a centuries-old technique. In 1798 English physicist Henry Cavendish measured the strength of gravity by dangling a barbell-shaped bob on the end of a fiber and watching it twist as one end came close to a heavy object. Now, Heckel and colleagues at the University of Washington have employed a souped-up version of Cavendish's "torsion balance" to search for background fields that interact with an electron's spin. The bob is a symmetrical assemblage of pieces of magnets arranged so that a majority of electrons spin in one direction. Crucially, the bob has no net magnetism, so it won't interact with the inevitable stray magnetic fields. So far Heckel and colleagues have seen no unusual twists of their apparatus.

Physicists have also repeated the Michelson- Morley experiment. Michelson and Morley reasoned that because Earth spins in the light-carrying ether, to an earthbound observer light should travel at different speeds depending on whether it is zipping north-south or east-west. SME's background fields could produce similar effects. Michelson and Morley used light beams and mirrors; today researchers employ "resonators" that ring with microwaves much as bells ring with sound. Two identical resonators are arranged perpendicularly and researchers compare their frequencies, achieving 10 million times better sensitivity than the original experiment, says John Lipa of Stanford University in California. Just as Michelson and Morley caught no whiff of the ether, modern experimenters have found no trace of the SME background fields.

Researchers had planned to fly atomic clocks and resonators on the international space station, where they would have been far more sensitive than earthbound experiments. But NASA scuttled those plans last year when President George W. Bush set his sights on sending humans to Mars (*Science*, 30 January 2004, p. 615). "Basically, NASA shut down all the activities in physics on the space station," Lipa says. "That's politics."

A subtler beauty

Why are some physicists so keen to take on Einstein? Answers vary widely. Experimenters should test basic theoretical assumptions as rigorously as possible as a matter of principle, says Gerald Gabrielse of Harvard University, who led the efforts to compare protons and antiprotons. "If we were to find a violation," Gabrielse says, "the consequences of that would ricochet through physics, affecting our understanding of the structure of the universe in every way."

On the other hand, some particle theorists may be drawn to the matter because "there's not that much else to do," quips Roman Jackiw, a theoretical physicist at the Massachusetts Institute of Technology in Cambridge. Particle theorists have little fresh and challenging data to gnaw on, Jackiw says, although that should change when an accelerator known as the Large Hadron Collider powers up at CERN in 2007.

To Kostelecký, the architect of SME, the allure is aesthetic. Special relativity states that spacetime possesses a kind of perfect symmetry, like an infinite plane so featureless that it's impossible to tell where you are and which direction you're facing. In special relativity, the symmetry extends to time, too, so that space and time mix together into a single seamless whole. That "Lorentz symmetry" is so elegant most physicists assume it's true. But "nature's beauty is more subtle than that perfect symmetry," Kostelecký says. "For me it may make nature more beautiful if it is *almost* Lorentz symmetric."

That sentiment might have intrigued Einstein, who often drew inspiration from his own sense of the beauty of nature and of physical theories. Perhaps he would have followed the thought to deep new insights, just as he surfed an imaginary light wave to one of the most profound ideas ever conceived.

–Adrian Cho

ILLUSTRATION: ADAPTED FROM BLUHM, KOSTELECKÝ, LANE, RUSSELL, *PHYSICAL REVIEW LETTERS* **88** (2002)

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