VIOLATIONS OF RELATIVITY could be manifest in the ticking rates of mirror-image, antimatter clocks and the stretching of matter along specific directions.

THE SEARCH FOR
RELATIVITY VIOLATIONS

To uncover evidence for an ultimate theory, scientists are looking for infractions of Einstein's once sacrosanct physical principle

By Alan Kostelecký

Relativity lies at the heart of the most fundamental theories

of physics. Formulated by Albert Einstein in 1905, relativity is built on the key idea that physical laws take the same form for any inertial observer—that is, for an observer oriented in any direction and moving at any constant speed. The theory predicts an assortment of well-known effects: among them, constancy of the speed of light for all observers, slowing of moving clocks, length contraction of moving objects, and equivalence of mass and energy ($E = mc^2$). These effects have been confirmed in highly sensitive experiments, and relativity is now a basic, everyday tool of experimental physics: particle colliders take advantage of the increase in mass and lifetime of fast particles; experiments with radioactive isotopes depend on the conversion of mass into energy. Even consumer electronics is affected—the Global Positioning System must allow for time dilation, which alters the rates of clocks on its orbiting satellites.

In recent years, however, motivated by attempts to combine all the known forces and particles into one ultimate unified theory, some physicists have been investigating the possibility that relativity's postulates provide only an approximation of nature's workings. The hope is that small relativity violations might offer the first experimental signals of the long-sought ultimate theory.

The unchanging quality, or invariance, of physical laws for different observers represents a symmetry of space and time (space-time), called Lorentz symmetry after Dutch theoretical physicist Hendrik Antoon Lorentz, who studied it beginning in the 1890s. A perfect sphere illustrates an ordinary symmetry, what is known as symmetry under rotations: no matter how you turn it, the sphere looks the same. Lorentz symmetry is not based on objects looking the same but expresses instead the sameness of the laws of physics under rota-

DAVID EMMITE PHOTOGRAPHY

Relativity Obeyed

a

b

c
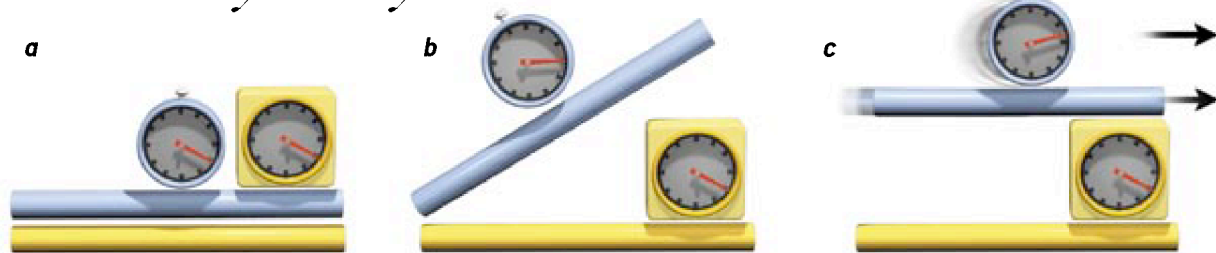
Lorentz symmetry is a fundamental property of the natural world that is of supreme importance for physics. It has two components: rotational symmetry and boost symmetry. Imagine that we have two rods made of dissimilar materials but having identical lengths when placed side by side and two clocks operating by different mechanisms that keep identical time (*a*). Rotational symmetry states that if one rod and one clock are rotated relative to the others, the rods nonetheless retain identical lengths and the clocks remain in sync (*b*). Boost symmetry considers what happens when one rod and one clock are "boosted" so that they move at a constant velocity relative to the other two, which here remain at rest. Boost symmetry predicts that the moving rod will be shorter and that the moving clock will run slower by amounts that depend in a precise way on the relative velocity (*c*). When space and time are combined to form spacetime, boost symmetry actually has almost identical mathematical form to rotational symmetry. A closely related symmetry is CPT symmetry, where the letters stand for charge conjugation, parity inversion and time reversal. This predicts that if a clock is replaced by its antimatter equivalent (charge reversal), which is also inverted (parity) and running backward in time, the two will keep identical time (*d*). A mathematical theorem demonstrates that for a quantum field theory, CPT symmetry must hold whenever Lorentz symmetry is obeyed.

d

Clock

Parity-
inverted
antimatter
clock
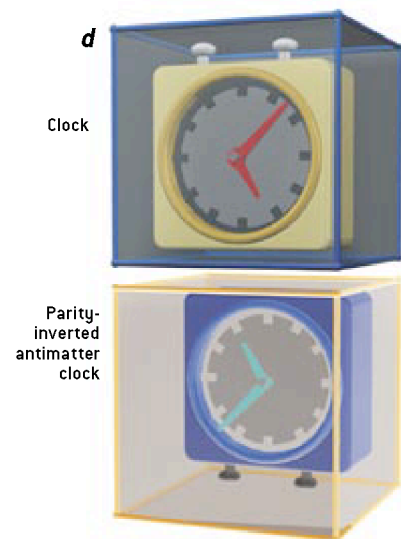
Relativity Violated
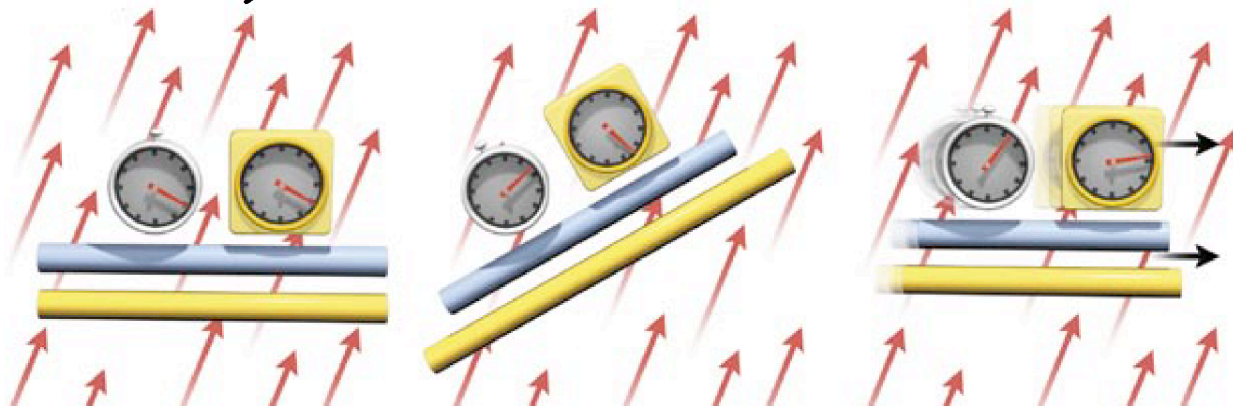
Broken Lorentz symmetry can be represented by a field of vectors throughout spacetime. Particles and forces have interactions with this vector field (*arrows*) similar to the interaction of charged particles with an electric field (which is also a vector field). As a result, unlike the Lorentz symmetric case, all directions and all velocities are no longer equivalent. Two dissimilar rods that have equal lengths at one orientation relative to the vector field (*left*) may shrink or expand at another orientation (*center*). Similarly, two dissimilar clocks that are synchronized at the first orientation may run slow or fast at the second orientation. In addition, dissimilar rods and clocks that are boosted (*right*) may undergo different length contractions and time dilations depending on their materials and the direction and magnitude of the boost.

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tions and also under boosts, which are changes of velocity. An observer sees the same laws of physics at play, no matter what her orientation (rotation) and no matter what her velocity (boost). When Lorentz symmetry holds, spacetime is isotropic in the sense that all directions and all uniform motions are equivalent, so none is singled out as being special.

The Lorentz symmetry of spacetime forms the core of relativity. The details of how boosts work produce all the well-known relativistic effects. Before Einstein's 1905 paper, equations relating to these effects had been developed by several other researchers, including Lorentz, but they typically interpreted the equations as describing physical changes in objects—for example, bond lengths between atoms becoming shorter to generate length contraction. Einstein's great contributions included combining all the pieces and realizing that the lengths and clock rates are intimately linked. The notions of space and time merge into a single concept: spacetime.

Lorentz symmetry is a key element in the very foundations of our best description of the fundamental particles and forces. When combined with the principles of quantum mechanics, Lorentz symmetry produces a framework called relativistic quantum field theory. In this framework, every particle or force is described by a field that permeates spacetime and has the appropriate Lorentz symmetry. Particles such as electrons or photons exist as localized excitations, or quanta, in the relevant field. The Standard Model of particle physics, which describes all known particles and all known nongravitational forces (the electromagnetic, weak and strong forces), is a relativistic quantum field theory. The requirements of Lorentz symmetry strongly constrain how the fields in this theory can behave and interact. Many interactions that one could write down as plausible-looking terms to be added to the theory's equations are excluded because they violate Lorentz symmetry.

The Standard Model does not include the gravitational interaction. Our
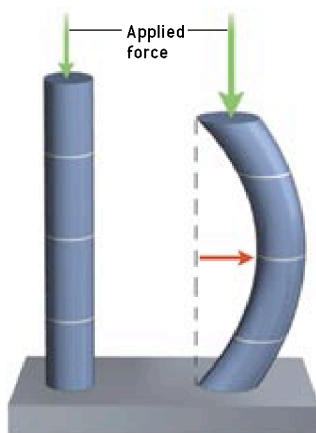
Applied force

SPONTANEOUS SYMMETRY BREAKING occurs when a completely symmetric set of conditions or underlying equations gives rise to an asymmetric result. For example, consider a cylindrical stick with a force applied vertically (*left*). The system is completely symmetrical with respect to rotations around the axis of the stick. If a large enough force is applied, however, the system becomes unstable and the stick will bend in some direction (*right*). The symmetry breaking can be represented by a vector, or an arrow (*red*), that indicates the direction and magnitude of the bending. Lorentz violation involves the emergence of such vector quantities throughout spacetime.

best description of gravity, Einstein's general relativity, is also founded on Lorentz symmetry. (The term "general" means that gravity is included, whereas "special" relativity excludes it.) In general relativity, the laws of physics at any given location are the same for all observer orientations and velocities, as before, but the effects of gravity make comparisons between experiments at different locations more complicated. General relativity is a classical theory (that is, nonquantum), and no one knows how to combine it with the basic Standard Model in a completely satisfactory way. The two can be partially combined, however, into a theory called "the Standard Model with gravity," which describes all particles and all four forces.
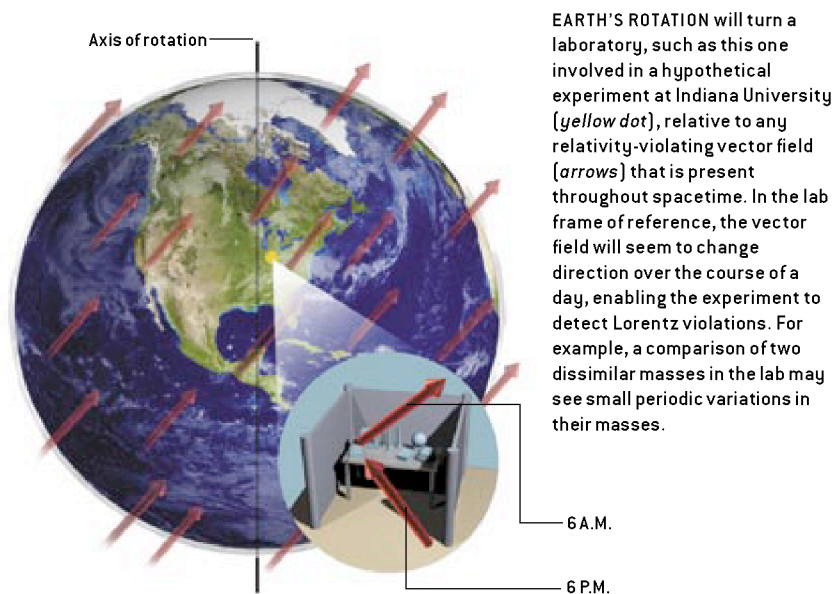
Unification and the Planck Scale

TOGETHER THIS MELDING of the Standard Model and general relativity is astonishingly successful in describing nature. It describes all established fundamental phenomena and experimental results, and no confirmed experimental evidence for physics beyond it exists [see "The Dawn of Physics beyond the Standard Model," by Gordon Kane, on page 4]. Nevertheless, many physicists deem the combination unsatisfactory. One source of difficulty is that although quantum physics and gravity each have an elegant formulation, they seem mathematically incompatible in their present form. In situations where both gravity and quantum physics are important,

such as the classic experiment in which cold neutrons rise against the earth's gravitational field, the gravity is incorporated into the quantum description as an externally applied force. That characterization models the experiment extremely well, but it is unsatisfactory as a fundamental and consistent description. It is like describing how a person can lift a heavy object, with the bones' mechanical strength and other properties accurately modeled and explained down to the molecular level, but with the muscles depicted as black-box machines that can supply a specified range of forces.

For these reasons and others, many theoretical physicists believe that it must be possible to formulate an ultimate theory—a complete and unified description of nature that consistently combines quantum physics and gravity. One of the first physicists to work on the idea of a unified theory was Einstein himself, who tackled this problem during the last part of his life. His goal was to find a theory that would describe not only gravity but also electromagnetism. Alas, he had tackled the problem too early. We now believe that electromagnetism is closely related to the strong and weak forces. (The strong force acts between quarks, which make up particles such as protons and neutrons, whereas the weak force is responsible for some kinds of radioactivity and the decay of the neutron.) It was only with experimental facts uncovered after Einstein's death that the strong and weak forces became characterized well enough for them to

Axis of rotation

6 A.M.

6 P.M.

EARTH'S ROTATION will turn a laboratory, such as this one involved in a hypothetical experiment at Indiana University (*yellow dot*), relative to any relativity-violating vector field (*arrows*) that is present throughout spacetime. In the lab frame of reference, the vector field will seem to change direction over the course of a day, enabling the experiment to detect Lorentz violations. For example, a comparison of two dissimilar masses in the lab may see small periodic variations in their masses.

be understood separately, let alone in combination with electromagnetism and gravity.

One promising and comprehensive approach to this ultimate theory is string theory, which is based on the idea that all particles and forces can be described in terms of one-dimensional objects ("strings"), along with membranes of two dimensions and higher that are called branes [see "The String Theory Landscape," by Raphael Bousso and Joseph Polchinski, on page 40]. Another approach, known as loop quantum gravity, seeks a consistent quantum interpretation of general relativity and predicts that space is a patchwork of discrete pieces (quanta) of volume and area [see "Atoms of Space and Time," by Lee Smolin, on page 56].

Whatever the eventual form of the ultimate theory, quantum physics and gravity are expected to become inextri-

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cably intertwined at a fundamental length scale of about 10^{-35} meter, which is called the Planck length, after 19th-century German physicist Max Planck. The Planck length is far too small to be within the direct reach of either conventional microscopes or less conventional ones such as high-energy particle colliders (which probe "merely" down to about 10^{-19} meter). So not only is it very challenging to construct a convincing ultimate theory, but it is also impractical to observe directly the new physics it must surely predict.

Despite these obstacles, a route may exist for obtaining experimental information about the unified theory at the Planck scale. Minuscule indirect effects reflecting the new physics in the unified theory may be detectable in experiments of sufficient sensitivity. An analogy is the image on a television or computer screen, which is composed of many small, bright pixels. The pixels are small compared with the distance at which the screen is viewed, so the image appears smooth to the eye. But in special situations, the pixels become evident—for example, when a newscaster is wearing a tie with narrow stripes that trigger a Moiré pattern on the screen. One class of such "Moiré patterns" from the Planck scale is relativity violations. At macroscopic distances, spacetime ap-

pears Lorentz-invariant, but this symmetry may be broken at sufficiently small distances as a consequence of features of the unification of quantum physics and gravity.

The observable effects of Planck-scale relativity violations are likely to lie in the range of 10^{-34} to 10^{-17}. To gain some feeling for these numbers, consider that the thickness of a human hair is about 10^{-30} of the distance across the observable universe. Even 10^{-17} is roughly the ratio of a hair's thickness to the diameter of Neptune's orbit. The detection of relativity violations therefore requires some of the most sensitive experiments ever performed.

Another fundamental spacetime symmetry that could be violated is so-called CPT symmetry. This symmetry holds when the laws of physics are unaffected when three transfomations are all applied at once: interchange of particles and antiparticles (charge conjugation, C), reflection in a mirror (parity inversion, P) and reversal of time (T). The Standard Model obeys CPT symmetry, but theories with relativity violations may break it.

Spontaneous Violations

HOW MIGHT RELATIVITY violations emerge in the ultimate theory? One natural and elegant mechanism is called spontaneous Lorentz violation. It has similarities to the spontaneous breaking of other kinds of symmetry, which occurs whenever the underlying physical laws are symmetrical but the actual system is not. To illustrate the general idea of spontaneous symmetry breaking, consider a slender cylindrical stick, placed vertically with one end on the floor [see illustration on preceding page]. Imagine applying a force vertically downward on the stick. This situation is completely symmetrical under rotations around the axis of the stick: the stick is cylindrical, and the force is vertical. So the basic physical equations for this situation are symmetrical under rotation. But if sufficient force is applied, the stick will bend in some particular direction, which spontaneously breaks the rotational symmetry.

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In the case of relativity violations, the equations describing the stick and the applied force are replaced by the equations of the ultimate theory. In place of the stick are the quantum fields of matter and forces. The natural background strength of such fields is usually zero. In certain situations, however, the background fields acquire a nonzero strength. Imagine that this happened for the electric field. Because the electric field has a direction (technically, it is a vector), every location in space will have a special direction singled out by the direction of the electric field. A charged particle will accelerate in that direction. Rotational symmetry is broken (and so is boost symmetry). The same reasoning applies for any nonzero "tensor" field; a vector is a special case of a tensor.

Such spontaneous nonzero tensor fields do not arise in the Standard Model, but some fundamental theories, including string theory, contain features that are favorable for spontaneous Lorentz breaking. The idea that spontaneous Lorentz breaking and observable relativity violations could occur in string theory and field theories with gravity

was originally proposed in 1989 by Stuart Samuel of the City College of New York and me. It was extended in 1991 to include spontaneous CPT violation in string theory by Robertus Potting of Algarve University in Portugal and me. Since then, various additional mechanisms have been proposed for relativity violations arising in string theory and in other approaches to quantum gravity. If spontaneous Lorentz breaking or any other mechanisms do turn out to be part of the ultimate fundamental theory, the concomitant relativity violations could provide the first experimental evidence for the theory.

Standard Model Extension

SUPPOSE THAT the fundamental theory of nature does contain Lorentz violation, perhaps with CPT violation, through some mechanism. How would this manifest itself in experiments, and how can it be related to known physics? To answer these questions, we would like to have a general theoretical framework that encompasses all possible effects and that can be applied to analyze any experiment. With such a framework,

specific experimental parameters can be calculated, different experiments can be compared, and predictions can be made for the kind of effects to be expected.

Certain criteria guide our construction of this framework. First, all physical phenomena should be independent of the particular coordinate system used to map out space and time. Second, the experimental successes of the Standard Model and general relativity mean that any Lorentz and CPT violations must be small. By following these criteria and using only the known forces and particles, we are led to a set of possible terms—possible interactions—that could be added to the equations of the theory. Each term corresponds to a particular tensor field acquiring a nonzero background value. The coefficients that specify the magnitudes of these terms are unknown, and indeed many might be zero when the ultimate theory is known.

The end result is a theory called the Standard Model Extension, or SME. The beauty of this formulation is its generality: whatever your philosophical or physical preferences for the origin of relativity violations, the resulting effects in nature

ORBITING LABORATORIES

Studying Space in Space
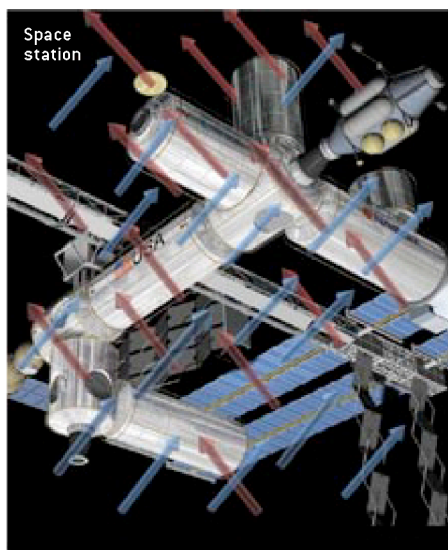
Space station

On satellites such as the space station will be experiments that seek evidence of Lorentz violations in comparisons of clocks. The illustration shows the case of two relativity-violating vector fields (*red* and *blue arrows*) with different interactions with particles. Depicted below is a comparison between an atomic clock (*represented by an atom*) and a clock based on light or microwaves (*wavy lines*) in a resonant cavity. The light and electrons (*red*) interact with the red vectors, whereas protons (*blue*) interact with the blue vectors. As the space station rotates, these changing interactions cause the clocks to go in and out of sync, revealing the Lorentz violation. The 92-minute rotation of the space station provides for much faster and more sensitive data taking than a stationary Earth-based experiment.

Electron

Neutron

Proton

Atom

Vector fields

Light in resonant cavity
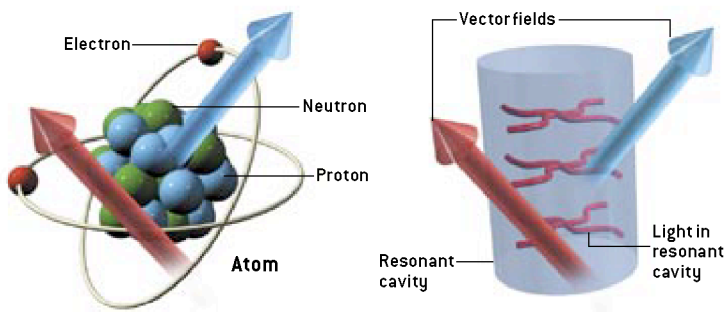
Resonant cavity

Toppling the Giant

Everyone wants to get a piece of Einstein. Two of the three most common crackpot missives received by scientists and science magazines involve Einstein: claims to have a unified theory (succeeding where Einstein failed) and claims to have proved his theories false. (The third big class of craziness: perpetual-motion machines and infinite-energy sources.) Like cannibals seeking the strength and life spirit of their victims, these misguided amateurs seem to think that by outdoing or disproving Einstein they will acquire all his prestige and acclaim. Of course, all that they disprove is their own competence with basic relativity.

But the crazies are not the only iconoclasts. Many serious and well-qualified researchers also seek to go beyond Einstein, in the way that he went beyond Galileo and Newton. The accompanying article by Alan Kostelecký describes the experimental search for departures from Einsteinian relativity. The analysis he discusses is based on a general "Standard Model Extension" in which all plausible relativity-violating terms are added to the equations of particle physics. This all-encompassing model covers every possible deviation that could trickle down to everyday physics from the high-energy pinnacle of the (as yet undiscovered) ultimate unified theory.

Yet certain putative breaches of relativity have attracted specific attention. One class of theories goes by the name "doubly special relativity," which has been studied by Giovanni Amelino-Camelia of the University of Rome since 2000 and later by Lee Smolin of the Perimeter Institute for Theoretical Physics in Waterloo, Ontario, João Magueijo of Imperial College London and others. Magueijo, incidentally, fits the label "iconoclast" to a T—as is apparent from his argumentative book *Faster Than the Speed of Light.*

Doubly special relativity is inspired by quantum gravity theories such as loop quantum gravity [see "Atoms of Space and Time," by Lee Smolin, on page 56], and it imposes a second kind of "speed limit" that works in conjunction with the conventional
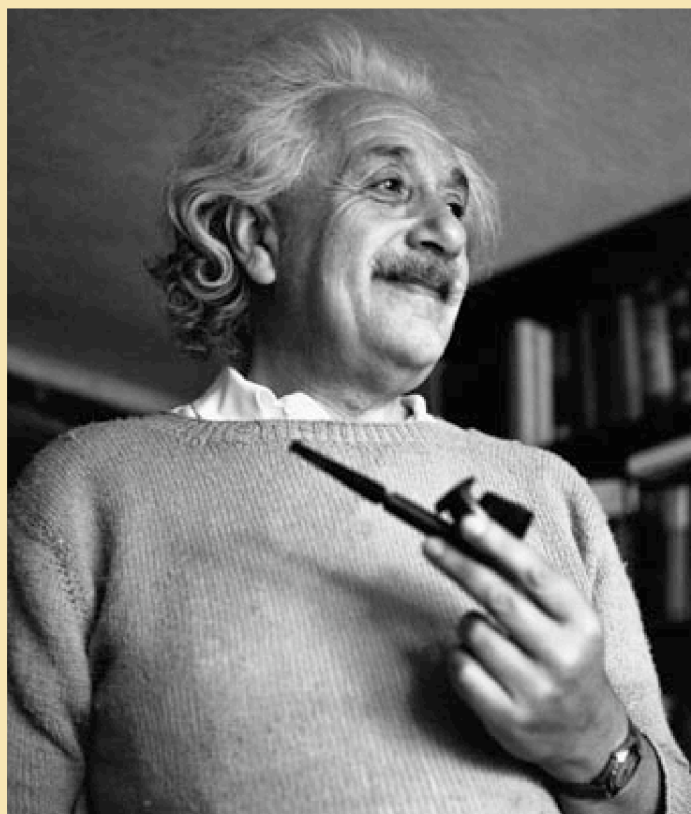
TOWERING FIGURE of Albert Einstein provides a tempting target for physicists of all stripes. He would perhaps look with approval on these efforts to go beyond his theories.

barrier of the speed of light in a vacuum, also known as *c*. The idea is that at very short distances the smooth continuity of spacetime should break down into something more granular—like grains of

must be described by the SME, because it contains all viable modifications and generalizations of relativity that are compatible with the Standard Model and the known behavior of gravity.

To visualize the effects of Lorentz violation, it is useful to think of spacetime as having an intrinsic orientation. In the case of a vector field causing a particular term in the SME equations, the orientation coincides with the direction of the vector field. The more general case of a tensor field is similar but more complicated. By virtue of couplings to these background fields, the motions and interactions of particles acquire a directional dependence, like charged particles moving in an electric

or a magnetic field. A similar visualization works for CPT violation, but in this case the effects occur because particles and antiparticles have different couplings to the background fields.

The SME predicts that the behavior of a particle can be affected by relativity violations in several ways. The particle's properties and interactions can depend on the direction it is moving (rotation violations) and on how fast it is going (boost violations). The particle may have spin, an intrinsic quantity of angular momentum, in which case the relativity-violating behavior can depend on the size and orientation of the spin. The particle can also fail to mirror its antiparticle (CPT violations). Each behavior can

vary depending on the species of particle; for instance, protons might be affected more than neutrons, and electrons not at all. These effects combine to produce a plethora of interesting signals that can be sought in experiments. A number of such experiments have begun, but so far none has provided conclusive evidence for relativity violations.

Ancient Light

ONE WAY TO OBTAIN exceptional sensitivity to relativity violations is by studying the properties of polarized light that has traveled billions of light-years across the cosmos. Certain relativity-violating interactions in the SME will change the polarization of light as

LUCIEN AIGNER *Corbis*

sand or the network of a spider's web. In quantum physics, short distances and short times correspond to high momenta and high energies. Thus, at sufficiently high energy—the so-called Planck energy—a particle should "see" the graininess of spacetime. That violates relativity, which depends on spacetime being smooth down to the tiniest size scales. Reflecting this, in a doubly special theory, just as a particle cannot be accelerated beyond c, it cannot be boosted beyond the Planck energy.

Some of these models predict that extremely high frequency light should travel faster than lower-frequency light. Experimenters are looking for that effect in light from distant explosions called gamma-ray bursts.

But skeptics are unconvinced that these theories are well founded. Some researchers argue, for example, that the equations are physically equivalent to ordinary relativity, just dressed up in enough complexities for that to be unobvious. The proof of the pudding will have to come from a rigorous derivation of such a theory from something more fundamental, such as string theory or loop quantum gravity. Not to mention experimental evidence.

Another infraction that some have contemplated is that c itself has varied over the history of the universe. John W. Moffat of the University of Toronto studied models of this type in the early 1990s, and Magueijo has been a more recent champion of them. If c had been much greater in the very early moments of the big bang, certain effects could have propagated at an extremely fast rate, which would solve some cosmological puzzles.

If c varies, so, too, does the fine structure constant, alpha, which is a dimensionless number that specifies the strength of the electromagnetic interaction. Alpha can be expressed in terms of c, Planck's constant and the charge of the electron. Alpha can therefore also change with c remaining constant, which might not infringe on relativity but would be equally seismic. Such variation in alpha could occur in string theory, where the magnitude of alpha

depends on the precise structure of extra tiny dimensions that are appended to the four dimensions of space and time that we know and love [see "The String Theory Landscape," by Raphael Bousso and Joseph Polchinski, on page 40].

The possibility that alpha might change was considered as long ago as 1955, by the great Russian physicist Lev Landau. Today physicists and astronomers are looking at ancient light from distant quasars for evidence that alpha was slightly different eons ago. Changing alpha would subtly alter the frequency of light emitted or absorbed by atoms and ions. Most searches for such shifts have turned up empty thus far. One exception is the results of a group led by John K. Webb of the University of New South Wales in Australia. Those researchers have used a novel method of analyzing the data to achieve finer precision and have reported evidence (albeit statistically somewhat weak) of shifts: between eight billion and 11 billion years ago, alpha appears to have been about six parts in a million feebler than it is today. Such a minute variation is hard to reconcile with the string theory explanation, which predicts long-term stability of constants such as alpha, punctuated by occasional catastrophic changes of great magnitude.

Some researchers, however, assert that the precision claimed by the new method is not correct and that the "shifts" are just statistical fluctuations. In March 2004 a team of astronomers led by Patrick Petitjean of the Institute of Astrophysics of Paris and the Observatory of Paris and Raghunathan Srianand of the Inter-University Center for Astronomy and Astrophysics in Pune, India, reported using the traditional methods pushed to the limit. They concluded that as far back as 10 billion years, alpha has changed by less than 0.6 part in a million, contradicting the claims of Webb and company.

So far then, Einstein has withstood all challengers. The iconoclasts will have to keep looking for the first chink in his armor.
—Graham P. Collins, staff writer

it travels through otherwise empty space. The change grows as the light travels greater distances.

In the SME, the dominant relativity violations involving light include both ones that break CPT and ones that preserve it. Those that break CPT are expected for technical theoretical reasons to be absent or negligible, and studies of cosmological data have confirmed this down to a sensitivity of 10^{-42}. About half the CPT-preserving relativity violations for light would be observable by measuring cosmological polarization: the change in polarization as the light travels would depend on the color of the light. At Indiana University, Matthew Mewes and I have searched for this ef-

fect in polarization data of infrared, visible and ultraviolet light from distant galaxies, obtaining a sensitivity of 10^{-32} on the coefficients controlling these violations.

The remaining relativity violations for light can be measured in the laboratory using modern versions of experiments similar to the classic Michelson-Morley test of relativity (named after physicist Albert Michelson and chemist Edward Morley). The original Michelson-Morley experiment sent two beams of light at right angles and verified that their relative speed is independent of direction. The most sensitive experiments nowadays use resonant cavities; for example, rotating one on a turntable and

searching for changes in the resonant frequency as it rotates. John A. Lipa's group at Stanford University uses superconducting cavities to study the properties of microwave resonances. Achim Peters of Humboldt University in Berlin, Stephan Schiller of Düsseldorf University in Germany and their collaborators use laser light in sapphire crystal resonators. These experiments and similar ones by other groups have already achieved sensitivities of 10^{-15} to 10^{-11}.

Clock-Comparison Experiments
EXCEPTIONAL SENSITIVITY to relativity violations has also been achieved

Antimatter Experiments

Hydrogen
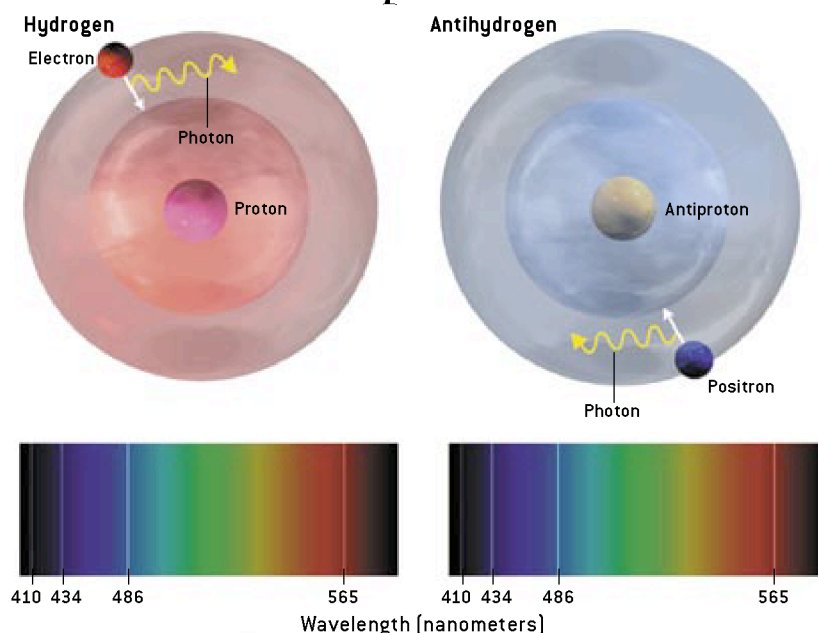
Antihydrogen

Antimatter should behave in identical fashion to matter if a form of spacetime symmetry called CPT invariance holds. Two experiments at CERN near Geneva are testing this hypothesis using antihydrogen atoms. A hydrogen atom emits light with a characteristic color or wavelength when its electron drops from a higher energy level to a lower one (*top left*). The same process in antihydrogen (*top right*) should emit the same color light (photons are their own antiparticles, so it is still a photon that is emitted). Thus, if CPT invariance holds, antihydrogen and hydrogen should have identical emission spectra (*bottom*). The CERN experiments will actually use absorption of ultraviolet laser light (the inverse of the emission process shown here) and transitions involving microwaves, all of which should also be identical for hydrogen and antihydrogen. Any discrepancy would be a signal of CPT violation, which in turn implies Lorentz violation.

in clock-comparison experiments, which search for changes in the ticking rate of a clock depending on its orientation. The typical basic "clock" is an atom in a magnetic field, and the ticking rate is the frequency of a transition between two of the atom's energy levels that depends on the strength of the magnetic field. The orientation of the clock is defined by the direction of the applied magnetic field, which is usually fixed in the laboratory and so rotates as the earth rotates. A second clock monitors the ticking rate of the first one. The second clock is often taken to be a different type of atom undergoing the same kind of transition. The ticking rates (the transition frequencies) have to be af-

fected by different amounts for the violation to become apparent.

To date, the most sensitive experiments of this type have been performed in Ronald Walsworth's laboratory at the Harvard-Smithsonian Center for Astrophysics. These experiments have attained the remarkable sensitivity of 10^{-31} to a specific combination of SME coefficients for neutrons. Walsworth's group mixes helium and neon in a single glass bulb and turns both gases into masers (microwave lasers), a difficult technical feat. The frequencies of the two masers are compared.

Various clock-comparison experiments with atoms as clocks have been performed at other institutions, achiev-

ing sensitivities of 10^{-27} to 10^{-23} for different types of relativity violations involving protons, neutrons and electrons. Other experiments have used (instead of atoms) individual electrons, positrons (antielectrons), negatively charged hydrogen ions and antiprotons in electromagnetic traps, and muonium (an "atom" made of an electron orbiting a positive muon particle).

Researchers have plans for several clock-comparison experiments on the International Space Station (ISS) and other satellites. These experiments would have a number of potential advantages, including easier access to all spatial directions. Typical ground-based clock-comparison experiments use the earth's rotation, but the fixed rotational axis limits sensitivity to some types of rotation violation. Because the ISS's orbital plane is inclined and precesses, all spatial directions could be sampled. Another advantage is that the ISS's orbital period of 92 minutes would allow data to be taken about 16 times as fast as a fixed earth-based experiment. (The ISS is often configured to keep the same side facing the earth, and thus it rotates every 92 minutes as well as orbiting in that time.)
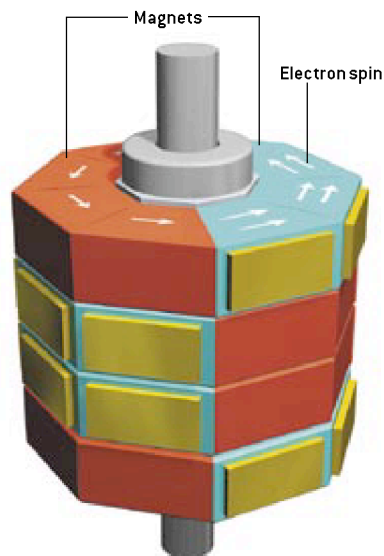
Antimatter

DIRECT TESTS FOR CPT violation can be performed by comparing properties of particles and antiparticles. One of the classic CPT tests involves a type of fundamental particle called the kaon. It turns out that the weak interaction causes a kaon gradually to convert into its antiparticle, the antikaon, and then back again. These kaon oscillations are so finely balanced that even a minuscule CPT violation would change them noticeably. Several large experimental collaborations have studied the oscillations of kaons to search for CPT violation. At present, the most sensitive constraint on Lorentz and CPT violation in kaons has been achieved by the KTeV Collaboration. This experiment used the giant Tevatron accelerator at Fermilab to create vast numbers of kaons. The results yielded two independent measurements

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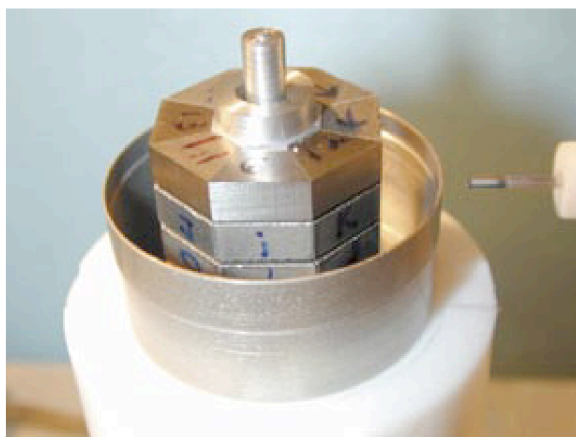
SPIN-COUPLED FORCES are investigated by a University of Washington experiment involving a torsion pendulum experiment (in which the hanging pendulum bob twists back and forth on its wire). The bob (*photograph above*) consists of rings of magnets made of two different materials (*red and blue at right*). The field of each magnet type has the same strength but is generated by a different quantity of electron spins (*arrows*). The magnetic field forms a closed loop with very little field outside the bob, reducing spurious signals caused by magnetic interactions. The electron spins, however, are unbalanced. If there is a sufficiently large relativity-violating vector field that interacts with electron spin, it will show up in perturbations of the bob's oscillations.

of SME coefficients at the level of 10^{-21}.

Two experiments, ATHENA and ATRAP, both taking place at CERN (the European laboratory for particle physics near Geneva), are under way to trap antihydrogen and compare its spectroscopic properties with those of hydrogen, which should be identical if CPT is preserved [*see box on opposite page*]. Any difference uncovered would represent a CPT violation and consequently a Lorentz violation.

High-sensitivity tests of relativity have also used objects made of materials in which the spins of many electrons combine to yield a net overall spin. (Think of each electron's "spin" as being a tiny compass needle. Opposite pointing needles cancel, but parallel ones add to give a larger total spin.) Such materials are common—for example, an overall spin produces the magnetic field of a bar magnet. In searching for Lorentz violation, however, the presence of a strong magnetic field is a hindrance. To circumvent this, Eric Adelberger, Blayne Heckel and their colleagues at the University of Washington have designed and built a spin-polarized ring of material that has a net electron spin but no external magnetic field [*see illustration above*]. The ring is used as the bob in a torsion pendulum, which twists back and forth

while suspended from a mounting on a rotating platform. A spin-dependent Lorentz violation would show up as a perturbation of the pendulum's oscillations that depends on the pendulum's orientation. This apparatus has been used to set the best current bounds on relativity violations involving electrons, at 10^{-29}.

It is possible that relativity violations have already been detected but have not been recognized as such. In recent years, ghostly fundamental particles called neutrinos have been shown to oscillate, which requires a modification of the minimal form of the Standard Model [see "Solving the Solar Neutrino Problem," by Arthur B. McDonald, Joshua R. Klein and David L. Wark, on page 22]. The oscillations are usually ascribed to small, previously unknown masses of neutrinos. But unusual oscillation properties for neutrinos are also

predicted in the SME. Theorists have shown that the description of neutrino behavior in terms of relativity violations and the SME may be simpler than the conventional description in terms of masses. Future analyses of neutrino data could confirm this idea.

The experiments I have discussed have demonstrated that Planck-scale sensitivities are attainable with existing techniques. Although no compelling evidence for relativity violations has emerged to date, comparatively few types of relativity violations have been studied so far. The next few years will see major improvements both in the scope of relativity tests (more coefficients measured) and in their depth (improved sensitivities). If relativity violations are finally discovered, they will signal a profound change in our understanding of the universe at its most fundamental level. 🅂🅰

MORE TO EXPLORE

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Back to the Future. Philip Ball in *Nature*, Vol. 427, pages 482–484; February 5, 2004.

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Special Relativity Reconsidered. Adrian Cho in *Science*, Vol. 307, pages 866–868; February 11, 2005.

Alan Kostelecký's Web site on Lorentz and CPT violation is at **www.physics.indiana.edu/ ~kostelec/faq.html**