"Ptolemy invented a universe and it lasted two thousand years. Newton invented a universe and it lasted two hundred years. Now Dr. Einstein has invented a new universe and no one knows how long this one is going to last."

George Bernard Shaw (1930)

A Touch of Gravity

by Eino-Ville Talvala

Once again, we present one of the best papers to come out of this year's Core 1 Science Writing course. The course is a requirement for all students, to help them improve their writing style and gain experience in communicating science to the general public (Alan Alda would approve). We'll feature another paper in our next issue.

Above: Illustration of Gravity Probe B in polar orbit. The satellite was built around the dewar, a thermos-like container full of liquid helium that holds the main instrumentation.

Chilling cold will surround translucent quartz spheres spinning silently in almost total isolation. Only the faint whispers of electric forces, and the ghostly touch of gravity, will reach into the cold vault of whirling gyroscopes. And, for a year and a half, they will spin ceaselessly while expectant scientists on Earth eagerly study the readouts of information streaming from the satellite orbiting far above them.

That satellite, called Gravity Probe B, carrying in its frigid interior some of the most precise measuring devices ever built, is currently in the final stages of construction at Stanford University and Lockheed Martin, with NASA providing funding and launch support. After more than 40 years of planning and building, it is now nearly ready, and is aimed to launch in April 2003. Its tale is deeply intertwined both with the discoveries in physics during the 20th century, and with the current efforts of physicists who are seeking the elusive "Theory of Everything."

The general theory of relativity, first put forward by Albert Einstein in 1916, overthrew Newton's law of gravity, which had been unable to predict accurately many of the observed phenomena that general relativity handles with grace. Einstein's theory, elegant in form (though often complex to apply), is one of the greatest theories ever conceived, and is his most powerful creation. It is also wrong.

General relativity and quantum mechanics, the two great theories of the 20th century, are fundamentally incompatible in structure. To reconcile the two, at least an amendment to general relativity is needed, or, as seems more likely now, a completely new theory must be created to explain the universe as we know it. Almost since the birth of these two theories, physicists everywhere have been seeking a Theory of Everything, also known as the Grand Unified Theory, which would combine quantum mechanics and general relativity into a theory that can describe all the interactions in the universe. This quest consumed Einstein's later life, but he never succeeded. So far, no one else has either.

But work has progressed, and today there are several candidates vying for the mantle of the Grand Unified Theory, many of them radically different from general relativity. And this is where Gravity Probe B steps in. (Gravity Probe A was a relativity experiment relating to the equivalence of gravitational and inertial mass, performed in 1976 by NASA and the Smithsonian Astrophysical Observatory.)

While many tests have been performed to verify general relativity, some of its predicted effects are almost too minuscule to observe. One such effect is called "frame dragging," and it is this effect that Gravity Probe B will measure. Frame dragging is a phenomenon that is created by massive spinning objects such as stars or, to a lesser extent, planets like Earth. Just as a heavy marble that is pressed against a tablecloth and spun will twist the tablecloth around itself, the spinning of Earth drags space-time, twisting it in the direction of Earth's spin. This effect has never been measured, because it is vanishingly small. The measurable effect of frame dragging is to twist the axis of rotation of a spinning object near Earth slightly over time, with the predicted magnitude of the effect being roughly 42 milliarc-seconds per year. (A single milliarc-second is equal to the apparent width of a lone human hair, as seen from 10 miles away.)

Gravity Probe B will contain four gyroscopes, the most accurate ones ever made. Once they are in orbit, they will be capable of detecting changes in their axes of rotation of 0.1 milliarc-seconds, a feat that cannot be equaled in ground-based experiments. Only in the microgravity of spaceflight can the gyroscopes spin without needing physical support—support that would destroy any hope of achieving the necessary accuracy, because of the mechanical vibrations and friction it would cause. The gyroscopes will be shielded from all

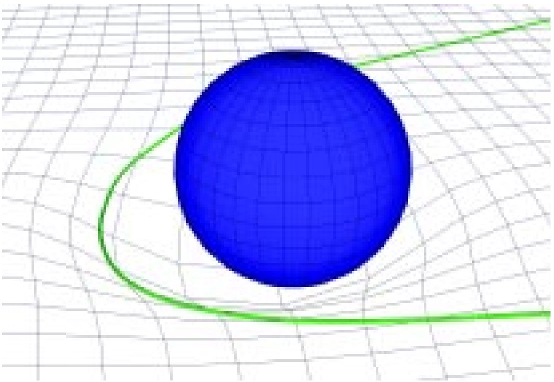
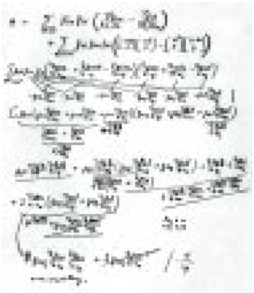


Illustration of curved space-time around a massive object. The green curve is the trajectory of a smaller mass that is deflected by the space-time curvature created by the heavy object.

external forces (such as solar wind, magnetic fields, and micrometeors) that could conceivably disturb them in the slightest and thus erase the faint traces of the frame-dragging effect.

With the measurement of the frame-dragging effect that Gravity Probe B will provide, any candidate Grand Unified Theory that predicts other values will be ruled out; if no frame-dragging effect is found, almost all the current theories will be shown to be lacking. Either way, the results will further the search for the ultimate goal of physics—the Theory of Everything. As stated at Gravity Probe B's project Web site (http://einstein.stanford.edu): "If we better understand the nature of mass and space, we may be able to do things previously undreamed of. So far, studies of relativity have yielded atomic clocks, guidance systems for spacecraft, and the Global Positioning System. We are limited only by our own imaginations when it comes to applications of science. Who knows? Maybe we can someday learn to manipulate gravity as thoroughly as we now manipulate electricity. We cannot foresee all that may come from a better understanding of space-time and mass-energy, but a theorem about these fundamental subjects must be thoroughly examined if we are to use it to our advantage."



A page of Einstein's research notes showing his efforts to develop the curvature scalar (ϕ at top left) for the general theory of relativity. From the third line down, he expands out only the first term on the second line. (Page 234, vol. 4, *The Collected Papers of Albert Einstein*; courtesy of The Albert Einstein Archives, the Hebrew University of Jerusalem.)

Into the past—the history of relativity

To understand the goals and significance of Gravity Probe B, a brief dip into the history of physics is in order. In the late 19th century, the laws of physics were thought to be nearly complete in their ability to explain the material world. Isaac Newton had described gravity 200 years earlier; James Maxwell had explained the phenomena of electricity and magnetism with his equations in 1873. Except for studies of a few minor unexplained phenomena, which were expected to be mopped up in a few years, it seemed to many that theoretical physicists would soon be out of a job. But this fate was not to be.

The problematic issues, such as the infinite values that arose in calculations of the energy output of an ideal heat-emitting object (a "blackbody"), and the stubborn undetectability of something called "the ether" (a medium that was thought to carry all light waves, as sound is carried by air), could not be easily resolved, and eventually resulted in a complete rewrite of the laws of physics.

In 1905, the first rewrite saw the light of day, as Einstein (with contributions from prominent scientists of the time such as Hendrik Lorentz and Jules-Henri Poincaré) published work that established the initial expression of the special theory of relativity. The theory did away with the ether, established the speed of light as the universal speed limit for mass and energy, and laid out his now-famous $E = mc^2$ equation. The theory was subsequently accepted by the scientific community, but soon a significant problem arose.

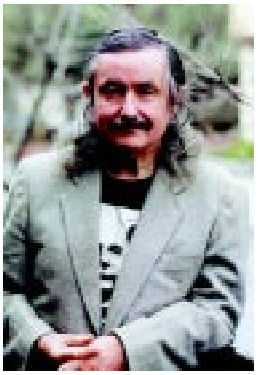
Special relativity contradicts Newton's law of gravity. According to Newton's law, the force of gravity acts instantaneously; if Earth were to become heavier in an instant, Newton predicted that everything in the solar system would feel the effect of this change in the same instant. This instantaneous response conflicts with special relativity's restriction that nothing can travel faster than light. Einstein immediately set out to resolve this conflict.

In 1916 he succeeded, publishing his general theory of relativity. According to Newton's laws, space was merely a backdrop upon which physics happened. In Einstein's view of the universe, space and time are active participants in the workings of physics. Whereas Newton described gravity as a force field that was created by all mass, Einstein saw gravity as the curvature of space-time itself: Mass tells space how to curve, and space tells mass how to move, as Princeton's John Wheeler put it. The diagram above left gives an idea of how this can happen.

To physicists, general relativity is conceptually simple and relies on only a few basic postulates and theorems. However, the mathematical framework for the theory consists of 10 "coupled hyperbolic-elliptic nonlinear partial differential equations," which take up several pages in their fully expanded form, and are likely to give any mathematician (not to mention everyone else) a severe headache. (Even Einstein found it difficult, see right.) However, when physicists are dealing with the effects of gravity sources that are weak (such as Earth, or just about anything less dense than a neutron star), the theory can be approximated into a simpler form. In this simpler form, a more intuitive description of frame dragging can be found.

The simpler equations look like those for electromagnetism. Electromagnetism describes electric and magnetic fields; with the simplified gravity equations, analogous "gravitomagnetic" and "gravitoelectric" fields can be derived from the overall gravity field. The gravitomagnetic field is created by moving masses, much as magnetic fields are created by moving electric charges. This field, created by Earth's spin, will interact with the spins of Gravity Probe B's gyroscopes, creating the frame-dragging effect (also known as the Lense-Thirring effect, named for the physicists who first isolated the effect from Einstein's equations).

Testing history



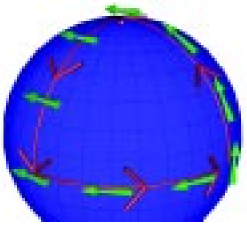
Francis Everitt, principal investigator for the Gravity Probe B project.

Gravity Probe B is intended to measure the frame-dragging effect to an accuracy of 0.3 percent, and will be the first direct measurement of the effect and of its magnitude. While many scientists feel confident that the results from Gravity Probe B will simply confirm Einstein's predictions, there are those who expect that the answer will be something quite different. As Nobel laureate Chen Ning Yang put it: "Einstein's general relativity theory, though profoundly beautiful, is likely to be amended . . . The Stanford experiment is especially interesting in that it focuses on the spin. I would not be surprised at all if it gives a result in disagreement with Einstein's theory."

Gravity Probe B is also measuring a second effect of general relativity, though this is one that has already been investigated. This "geodetic effect" is a much larger force than the frame-dragging effect. The geodetic effect is the sum of effects from two sources: Earth's gravitoelectric field, and the curvature of space-time around Earth itself.

Four-dimensional curvature of this type is hard to visualize, but the simplified analogy below can help explain its contribution to the geodetic effect. The combined effect of these two phenomena should result in a turn in the axis of the gyroscope's rotation of roughly 6 arc-seconds per year, a change of over 100 times that of the frame-dragging effect.

While the geodetic effect has been measured before by lunar laser-ranging experiments, Gravity Probe B will measure the effect to a precision of 75 parts per million (which is like measuring room temperature to three decimal places), which will be a vast improvement over previous measurements.



The red line follows a round trip made on a curved surface by a traveler holding a gyroscope. On returning to the starting point, the spin axis of the gyroscope (green arrow) would have turned 90 degrees from its original heading. Similarly, a satellite orbiting Earth travels through the curved space-time around it and, with each orbit, the orientation of the satellite changes slightly.

Combined, the two measurements that Gravity Probe B will make will probe the characteristics of spinning massive objects more deeply than any previous experiment, and give physicists new insights into the Grand Unified Theory.

The satellite itself

Gravity Probe B was envisioned in 1960 by three scientists working at Stanford University: Leonard Schiff and William Fairbank of the department of physics, and Robert Cannon of the department of aeronautics and astronautics. Together, they started a development group that, since 1962, has been led by Professor Francis Everitt (left), the principal investigator in charge of Gravity Probe B.

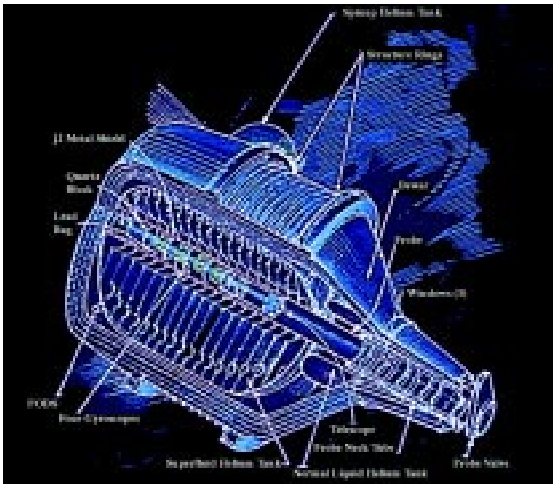
Because many of the requisite technologies did not exist at the start of the project, over the years the Gravity Probe B group has by necessity furthered the state of the art in dozens of fields. The group has realized large gains in cryogenics, gyroscope construction, and superconductor research. For example, a graduate student in the Gravity Probe B group developed a dewar that can be used to store the liquid helium the probe will need in orbit. This device has already been used in other satellites that need extreme cooling, such as the COBE satellite that first mapped the cosmic microwave background radiation.

There will only be one chance for the Gravity Probe B experiment to succeed, so the project has been studied over and over again, and every effort has been made to find any and all sources that might cause trouble. Numerous reviews by NASA, independent boards, and internal review groups have yet to find a detail that is not accounted for, a testament to the rigorousness of the planning for the project.

Beyond the technical challenges, Gravity Probe B has faced significant political obstacles. Due to the length of the project, it has often faced congressional scrutiny and budget-cut threats. It probably helps in his dealings with Congress that Professor Everitt looks very much a physicist in the style of Einstein; he even has a similar hairstyle.

So, after all this work and planning, what is the satellite like? The main structural element is the liquid-helium dewar, capable of holding 400 gallons of helium. (A dewar is a cryogenic container for storing very-low-temperature liquids and materials. Essentially, it is a large, complex thermos bottle.) The dewar contains the main science probe; this includes the gyroscopes, their readout systems, and the reference star-tracking telescope, which keeps the satellite oriented toward a guide star. The rest of the spacecraft is built around the dewar. This includes solar panels, control thrusters, and the computer systems.

In order for Gravity Probe B to work, the gyroscopes need to be shielded from all possible



A cross section of the liquid-helium dewar. Gravity Probe B carries four gyroscopes, placed along the spin axis of the satellite with high precision, and surrounded by lead bags to remove magnetic fields. The star-tracking telescope sits at the top of the main quartz block, looking out through transparent windows in the dewar's neck. The liquid helium is used for cooling and as a reaction mass for attitude control. © Barron Storey.

external forces besides gravity. This has required many ingenious design methods to eliminate outside influences on the gyros, and is the main source of complexity in the probe's design. The most important parameters that must be achieved by Gravity Probe B have been dubbed the Seven Near Zeros:

1. Low temperature. Liquid helium will cool the gyroscopes to 1.8 kelvins (–457.2 degrees Fahrenheit).
2. Low pressure. The gyroscope structure is surrounded by a cylindrical shell kept at a vacuum emptier than space (10^{-11} torr, or one hundred-trillionth of Earth's sea-level pressure).
3. Low magnetic field. Various shields will reduce the magnetic field inside the dewar to one ten-millionth of Earth's magnetic field (10^{-7} gauss).
4. Low gravity. Achieved by testing in space.
5. Low density variation. The gyroscopes are made of very uniform quartz to make them spin without any aberration.
6. Near-perfect sphericity. The gyroscopes are perfect spheres to 40 atomic layers, covered by a uniform layer of metal.
7. Near-perfect electric sphericity. The surface properties of the gyroscope remove any irregularity in the electric charge of the gyroscope.

The gyroscopes must be held at such low temperatures to maintain superconductivity, on which the gyroscope readout and magnetic shielding rely. Liquid helium will boil off constantly through a special porous plug in the dewar to maintain the science probe at its required temperature for up to 18 months. The boiled-off helium will also be recycled to be used in the precision-controlled thrusters for the satellite, allowing very fine adjustments to be made to the satellite's orientation to track the guide star exactly.

A completed gyro rotor, the size of a ping-pong ball, and its housing.

Because external magnetic fields (like Earth's field) destroy the accuracy of the gyroscopes' readouts, the probe's innards must be well insulated. This insulation is achieved with superconductors, materials that have no electrical resistance once they have cooled below a critical temperature, and that have properties that are very unusual. For one, a superconductor does not allow magnetic fields to pass through it. A hollow superconductor, therefore, will trap any magnetic field inside it permanently as soon as it becomes superconductive. In Gravity Probe B, superconducting lead bags are used to trap magnetic fields like this. The bags will be layered over the gyroscope housings, one on top of the next. They will then be expanded one by one, stretching the magnetic field trapped inside thinner and thinner, like a cook spreading out a lump of pizza dough.

The gyroscopes, consisting of a spinning rotor and the surrounding housing (bottom left), are triumphs of precision manufacturing: the rotors are smooth to within 40 atomic layers and are made of incredibly uniform fused quartz. Unlike, say, a pure metal sphere, quartz will not expand or contract with temperature (in contrast, small gaps must be left between lengths of metal railroad tracks because they are known to stretch on hot days); and quartz can be made to be very uniform in density, an important factor in making the gyroscopes spin without wobble. The gyroscope rotors, which will be secured to their housing during take-off, will free-float once the satellite is in orbit, and will never touch their housing after they have reached their operational speed of 10,000 rpm. The spin-up will be done by shooting supersonic helium gas past the gyroscope rotors, and will bring the gyros up to speed without harsh physical contact.

The experiment must also account for problems like the solar wind, which, even with its feeble push, could destroy the accuracy of the measurements. Therefore, the satellite is designed to track one of the gyroscope rotors, allowed to float freely in its cavity in the center of the satellite; the satellite will adjust its own orbit to keep the rotor centered in its housing, instead of exerting force on the rotor. Since the gyroscope is deep within the satellite, it will be protected from the solar wind, micrometeoros, and similar phenomena. The rotor will therefore trace a near-perfect orbit around Earth, and the satellite will follow along with it.

The gyroscope design has also had to answer one of the original paradoxes of the Gravity Probe B project: How can scientists measure the orientation of a gyro that they cannot touch? Because any physical contact with a spinning gyroscope rotor would destroy the required accuracy, some way to read the position of the gyroscope was needed that did not interfere with the gyroscope itself.

In the end, the answer depends on another property of superconductivity, discovered by Fritz London. A spinning superconductor acts like a very weak magnet, with the poles of the magnet precisely aligned with the axis of the spin. The gyroscope rotors are covered with a layer of niobium, a metal that will superconduct when it is cooled by liquid helium. Therefore, a precise, but very weak, magnetic pointer will be created that will allow scientists to determine the spin axis of the gyroscope. Incredibly sensitive magnetometers, called SQUIDs, for Superconducting QUantum Interference Devices, will utilize other superconductivity principles to detect the faint fields from the gyroscope rotors, and to transmit this information to the flight computers.

This tiny star-tracking telescope made of fused quartz is only 14 inches long, with a 5.6-inch-diameter primary mirror, but the ingeniously folded Cassegrain optics give it a focal length of 12 feet 6 inches.

The metal layer will also help to keep the gyroscopes centered in their housings. Three electrodes in the gyroscope housing can exert electric forces to support the rotor during spin-up, or in case a micrometeorite impacts on the satellite.

From the precise SQUID information, the scientists on Earth will be able to tell how the gyroscopes are oriented relative to the Gravity Probe B satellite. However, this won't do much good unless they also know how the satellite is oriented relative to the rest of the universe; otherwise, there will be no way to know how the gyroscopes have moved relative to Earth's gravitational field. To establish its orientation, the satellite will point toward a guide star, using a very precise star-tracking telescope, above left. The guide star's motion is well known, and can be compared to faraway galaxies and quasars, which provide a fixed reference frame for the experiment.

The accuracy of the telescope must match the accuracy of the gyroscopes, so the telescope must be able to find the star with an error of, at most, 0.1 milliarc-seconds. From Earth, the chosen guide star (which is known in star catalogs as HR8703) has an apparent width of about 90 milliarc-seconds, so the telescope must do more than just point toward the star, it must find the center of the star to great accuracy.

The telescope, its supports, and the rest of the instrumentation inside the dewar, are made of quartz. New techniques to attach quartz to quartz were developed in the construction of the probe, including fusing separate blocks together so seamlessly that they look like they were carved from a single block. The resulting telescope is a thousand times more accurate than typical star-tracking telescopes, due in large part to the amazing stability of the fused quartz.

As of this writing, the heart of Gravity Probe B has been completed; everything inside the dewar is in place, and it has been cooled to operating temperature. Work is progressing on attaching the outer systems to the dewar and on verifying that everything works. So far, it looks good.

Toward the future

Gravity Probe B has a chance to either further confirm or, in one swift stroke, disprove general relativity, Einstein's greatest work. While physicists know that the theory must be amended, nobody has yet made a direct physical measurement that disagrees with general relativity. A measured value of the frame-dragging effect, and a very precise measurement of the geodetic effect, will one way or another rule out many possible Theories of Everything. While all theories, of course, must predict results that would be nearly identical to those of general relativity, the effects of spinning objects are an area in which the theories often disagree. Nothing helps out a theory more than a new measurement that agrees with a value the theory has predicted beforehand.

It is ironic that, in the end, measurements made from small spinning balls, isolated only with great ingenuity from the forces of the rest of the cosmos, will help uncover the underlying laws and structure of the entire universe. But until Gravity Probe B launches and spins up its gyros, the universe will be able to hide one of its great secrets for a bit longer. After so many years of work, Gravity Probe B has the patience to wait. □

Eino-Ville (Eddy) Talvala, a senior majoring in electrical engineering, has more than just an academic interest in Gravity Probe B: he's been helping to develop one of its subsystems during his summer breaks. This is his third summer at Stanford, but it will probably be his last, as the satellite is scheduled for launch next April by a Delta II rocket from Vandenberg Air Force Base. His mentor, Steven Frautschi, is professor of theoretical physics, and served as master of student houses from 1997 until July this year.