Can scientists' "theory of everything" really explain all the weirdness the universe displays? /// BY EDWARD WITTEN

Astronomers have wrapped up cosmic history in a neat package. Or so it might seem. Some 12 to 14 billion years ago, the universe came into existence — along with space and time themselves. A fraction of a microsecond later, inflation set in, and for a brief period, the cosmos expanded at an explosive rate. Within a billion years, galaxies began to form with the aid of dark matter, which still holds them together. And now, a mysterious force known as dark energy seems to be taking over, accelerating the universe's ongoing expansion.

Yet this picture just skims the surface. Scientists aim to dig deeper, to understand why things happened the way they did. What was the Big Bang, and how could time just begin? What caused cosmic inflation? And what, exactly, are dark matter and dark energy?

Many scientists believe the answers to these questions are tied up with some of the deepest unsolved problems in physics. A thirty-year-old framework known as string theory promises new insights and offers hope that answers to at least some of these puzzles may be on the horizon.

The story begins early in the 20th century, when Albert Einstein drastically changed our notions about space and time. In Einstein's theory, space and time, which in everyday experience seem completely different, were unified into a strange new concept that came to be called space-time. His ideas have held up well — almost everything else in our fundamental description of physics has changed since Einstein's day, but we still describe space-time using the concepts he introduced. Yet many scientists suspect this is destined to change and that new developments in the understanding of space-time will need to emerge before we can attack the grand puzzles ahead.

Actually, Einstein transformed our concepts of space and time with two startling revelations. The first upheaval came in 1905 with the theory of special relativity, which explored the strange behavior of matter moving near the speed of light. The theory showed how clocks carried on a rapidly moving spaceship slow down and the heartbeat of an astronaut almost stands still — as seen by an observer at rest.

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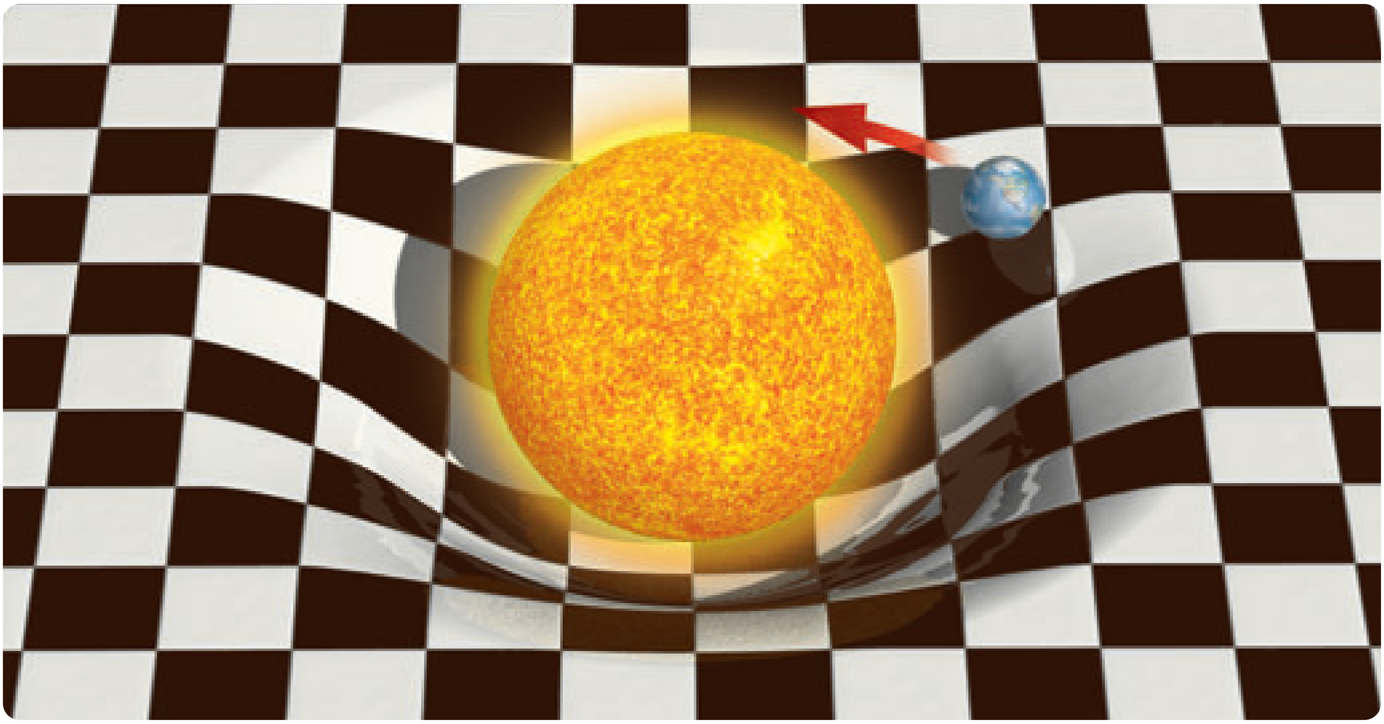
Universe

STRING THEORY suggests that particles in the universe are composed of loops of vibrating strings. Like a violin or piano string, one of these fundamental strings has many different harmonics. In string theory, harmonics correspond to different elementary particles. If string theory proves correct, electrons, photons, and neutrinos are different due to changes in the vibrations of the strings. ILLUSTRATION: *ASTRONOMY*: CHUCK BRAASCH


on a string



ACCORDING TO EINSTEIN, gravity arises because massive objects, like the Sun, warp space-time, causing smaller objects like Earth to orbit them.
ASTRONOMY: ROEN KELLY

Ten years later, when most scientists had barely recovered from the first shock, the second revolution arrived. In 1915, Einstein completed his greatest and most surprising achievement: the theory of gravity known as general relativity. According to general relativity, space-time is curved, and the curvature is created by matter. When planets travel in elliptical orbits around the Sun, for example, they are merely seeking the most direct paths in the curved geometry created by the Sun's gravity.

Surprising predictions from special relativity ranged from an ultimate speed limit — nothing can travel faster than the speed of light — to the famous formula, $E=mc^2$, that describes the equivalence of mass and energy. General relativity, on the other hand, predicted gravitational waves, black holes, the bending of light by the Sun, and the expansion of the universe.

After Einstein, further discoveries changed almost everything else in our understanding of physics. Scientists discovered new building blocks of matter and the surprising laws that govern their behavior. But all the new phenomena occurred, and all the new particles were found, in the space-time arena that Einstein had set forth.

In the 1920s, we learned that subatomic particles obey not Newton's laws of motion but the weird and wonderful laws of quantum mechanics, in which particles behave as waves and Heisenberg's uncertainty principle (you can know an electron's velocity or its position, but not both) gives everything a fuzziness nearly impossible to describe in words. By the mid-1970s, quantum theory was expanded into a theory of elementary particles — the standard model of particle physics — which in its own realm is every bit as successful as Einstein's theory.

By the 1970s, a clear division of labor existed in our understanding of physics. General relativity described large objects such as the solar system, galaxies, and the universe. Quantum mechanics, as elaborated in the standard model, described small objects such as atoms, molecules, and subatomic particles.

Physicists, however, are not satisfied having two different theories that work in two different realms. One reason is simply that big objects ultimately are made out of little objects. The same forces operate on both atoms and stars, for example, even though gravity is more obvious for stars while electricity and magnetism dominate in atoms. So it must be possible to combine the standard model and general relativity into a bigger, more complete theory that describes the behavior of both atoms and stars.

Moreover, the quest for unification has paid enormous dividends in the past. Both the standard model and general relativity were discovered, in large part, through efforts to unify earlier theories. Unfortunately, direct attempts to express general relativity in quantum mechanical terms have led to a web of contradictions, basically because the nonlinear mathematics Einstein used to describe the curvature of space-time clashes with the delicate requirements of quantum mechanics.

String theory to the rescue?

Occasionally, when scientists face a big problem like this one, someone disappears into an attic for seven years and emerges with an answer. That, more or less, is how Andrew Wiles proved Fermat's Last Theorem. In the case of quantum gravity, the "scientist in an attic" approach has never borne much fruit. Luck played a role instead: Physicists who originally had quite a different goal in mind stumbled onto a promising approach.

This came about in the early 1970s with the development of string theory. According to string theory, an elementary particle is not a point but a loop of vibrating string. Just like a violin or piano string, one of these "fundamental strings" has many different harmonics or forms of vibration. For a piano string, the

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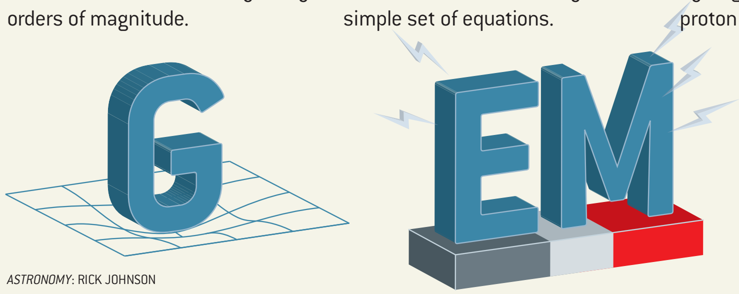
/// UNITING THE FOUR FUNDAMENTAL FORCES OF NATURE WITH STRING THEORY

GRAVITY describes the attractive force of matter. It is the same force that holds planets and moons in their orbits and keeps our feet on the ground. It is the weakest force of the four by many orders of magnitude.

ELECTROMAGNETISM describes how electricity and magnetic fields work. It also makes objects solid. Once believed to be two separate forces, it was discovered both could be described by a simple set of equations.

THE STRONG NUCLEAR FORCE is responsible for holding the nucleus of atoms together. Without this force, protons would repel one another so no elements other than hydrogen — which has only one proton — would be able to form.

THE WEAK NUCLEAR FORCE explains beta decay and the associated radioactivity. It also describes how elementary particles can change into other particles with different energies and masses.



ASTRONOMY: RICK JOHNSON

The equations that describe gravity, including Einstein's theory of general relativity, predict the behavior of objects on macroscopic scales extremely accurately. In the microscopic world, however, electromagnetism, the strong nuclear force, and the weak nuclear force dominate. Collectively, they provide the foundation of quantum mechanics. Because gravity is so weak at small scales compared to the other forces, particle physicists don't even bother to account for it in their experiments. To illustrate this, imagine a single proton lying on the floor and another suspended one yard (meter) above it. The strong nuclear force is so powerful that the top proton's attraction easily outmuscles the gravitational pull of the entire Earth.

Why try to unite the four forces in a single theory? Why not simply use Einstein's theory of general relativity to govern big things and quantum mechanics for little ones? Some concepts, such as the Big Bang or how black holes form, live in both domains. When we combine equations of the four forces to describe these ideas, our answers usually end up being either zero or infinity. Neither answer is worse; describing an object bigger than the (finite) universe — or one that doesn't exist — are both equally impossible.

Here's where string theory comes to the rescue. By adding seven hidden dimensions to the familiar three and another for time, plus antiparticles and a mirror set of particles called superparticles, the math starts to make sense. The force of gravity is diluted because it permeates into one or more of the hidden dimensions. Dark matter and dark energy also may invisibly shape our universe from these phantom dimensions.

So how do we know if string theory is real or just a mathematical abstraction? At this point, no one has devised an experiment that can prove or disprove it. Critics say there will never be such an experiment. Proponents, however, see such beauty and symmetry in the equations — as nature has revealed so often in the past — that it would be tragic if some form of string theory was not real. — *Tom Ford*

harmonics consist of a basic note — such as middle C — and its higher overtones (one, two, or several octaves higher). The richness of music comes from the interplay of higher harmonics. Music played with a tuning fork, which produces only a basic note, sounds harsh to the human ear.

In string theory, different harmonics correspond to different elementary particles. If string theory proves correct, all elementary particles — electrons, photons, neutrinos, quarks, and the rest — owe their existence to subtle differences in the vibrations of strings. The theory offers a way to unite disparate particles because they are, in essence, different manifestations of the same basic string.

How does this help us with gravity? In the early 1970s, calculations showed that one of the string's vibrational forms had just the right properties to be a graviton, the basic quantum unit of gravity. Curiously, like many of the most important discoveries in string theory, this one came about when a researcher made a technical calculation without realizing, at the time, the full implications of his work.

From little acorns grow mighty oaks. A quantum theory with gravitons must, according to arguments that physicists have known for years, incorporate the full structure of Einstein's theory — at least in circumstances involving astronomical bodies where general relativity successfully applies. (At the atomic level, such a theory has to depart from Einstein's, which doesn't work quantum mechanically.)

Back in the early 1970s, one of the pioneers of string theory, Italian physicist Daniele Amati, characterized the theory as "part of 21st-century physics that fell by chance into the 20th century." He meant that string theory had been invented by chance and developed by a process of tinkering, without physicists really grasping what was behind it. Amati surmised that a true understanding of the foundation of this remarkably rich theory would have to await the 21st century.

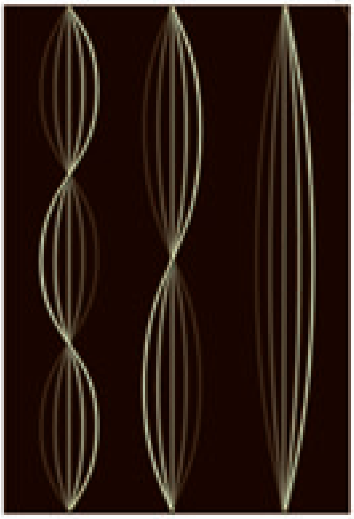
Thirty years later, we have a firmer grip on many issues, yet there's still much we don't understand at all — including the foundations of string theory. On the other hand, with the 21st century only just begun, we have yet to fall behind Amati's schedule!

The fuzziness of space-time

Perhaps the most basic thing we have learned about string theory is that it modifies the concepts of space-time that Einstein developed. This doesn't come as a complete surprise: Einstein based his theory of gravity on his ideas about space-time, so any theory that modifies Einstein's gravitational theory to reconcile it with quantum mechanics has to incorporate a new concept of space-time.

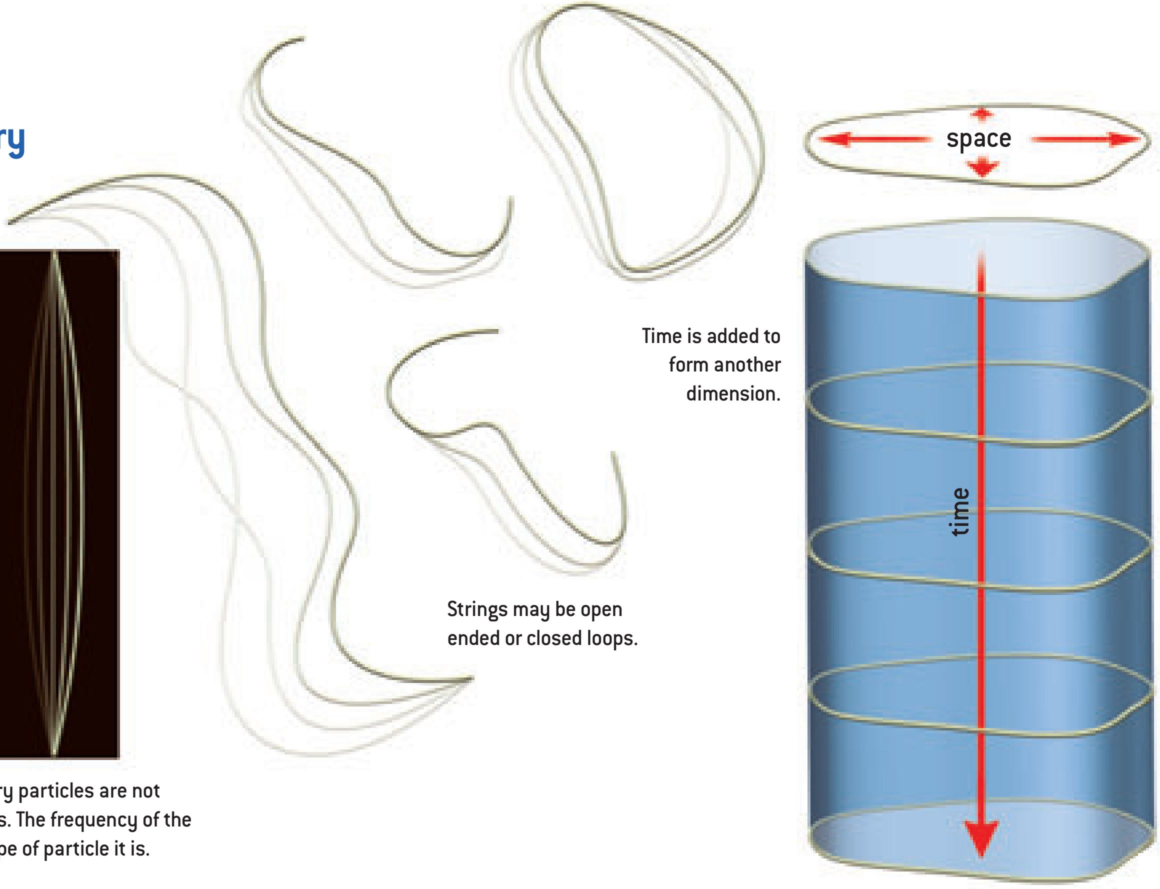
String theory actually imparts a "fuzziness" to all our familiar notions of space and time, just as Heisenberg's uncertainty principle imparts a basic fuzziness to classical ideas about the motion of particles. In ordinary quantum mechanics, interactions among elementary particles occur at definite points in space-time. In

The beauty of string theory



In string theory, elementary particles are not points but vibrating strings. The frequency of the string determines what type of particle it is.

ASTRONOMY: ROEN KELLY



string theory, things are different: Strings can interact just as particles do, but you cannot say quite when and where this occurs.

Even to a theoretical physicist, this kind of explanation raises more questions than it answers. String theory involves a conceptual jump that's large even compared with previous revolutions in physics. And there's no telling when humans will succeed in crossing the chasm.

Nevertheless, we really do understand one aspect of how string theory changes our notions of space-time. This involves a key part of string theory called supersymmetry. Finding supersymmetry offers cosmologists' best and brightest hope of proving that string theory has something to do with nature and is not just armchair theorizing.

In our everyday life, we measure space and time by numbers. For example, we say, "It is now 3 o'clock," "We are 200 feet above sea level," or "We live at 40° north latitude." This idea of measuring space and time by numbers is one bit of common sense that Einstein preserved. In fact, in his day, quantities that could be measured by numbers were all physicists knew about.

But quantum mechanics changed that. Particles were divided into bosons (like light waves) and fermions (like electrons or neutrinos). Quantities like space, time, and electric field that can be measured by numbers are "bosonic." Quantum mechanics also introduced a new kind of "fermionic" variable that cannot be measured by ordinary numbers. Fermionic variables are infinitesimal and inherently quantum mechanical, and as such are hard to visualize.

According to the idea of supersymmetry, in addition to the ordinary, familiar dimensions — the three spatial dimensions plus time — space-time also has infinitesimal or fermionic dimensions. If supersymmetry can be confirmed in nature, this will begin the process of incorporating quantum mechanical ideas into our description of space-time. But how can we ever know if supersymmetry is right?

Discovering supersymmetry

In a world based on supersymmetry, when a particle moves in space, it also can vibrate in the new fermionic dimensions. This new kind of vibration produces a cousin or "superpartner" for every elementary particle that has the same electric charge but differs in other properties such as spin. Supersymmetric theories make detailed predictions about how superpartners will behave. To confirm supersymmetry, scientists would like to produce and study the new supersymmetric particles. The crucial step is building a particle accelerator that achieves high enough energies.

At present, the highest-energy particle accelerator is the Tevatron at Fermilab near Chicago. There, protons and antiprotons collide with an energy nearly 2,000 times the rest energy of an individual proton. (The rest energy is given by Einstein's well-known formula $E=mc^2$.) Earlier in this decade, physicists capitalized on Tevatron's unsurpassed energy in their discovery of the top quark, the heaviest known elementary particle. After a shutdown of several years, the Tevatron resumed operation in 2001 with even more intense particle beams.

In 2007, the available energies will make a quantum jump when the European Laboratory for Particle Physics, or CERN (located near Geneva, Switzerland) turns on the Large Hadron Collider, or LHC. The LHC should reach energies 15,000 times the proton rest energy. The LHC is a multi-billion dollar international project, funded mainly by European countries with substantial contributions from the United States, Japan, and other countries.

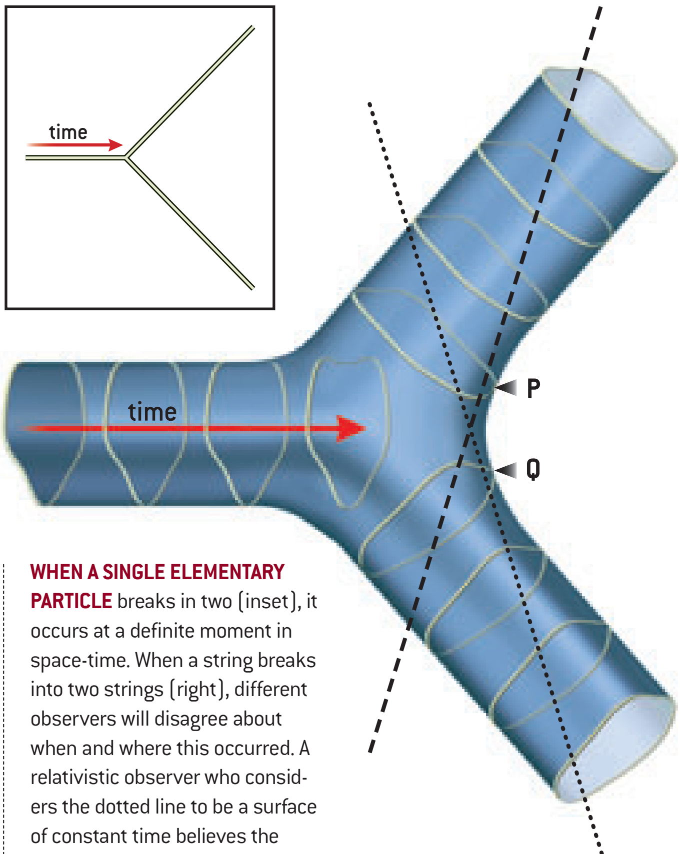
If our hunches prove correct, there's an excellent chance that supersymmetry lies within reach of the LHC, and maybe even of the Tevatron. Many physicists suspect the LHC will produce supersymmetric particles at a huge rate. If that happens, elementary particle physics will enter a completely new era, with the experimental study of phenomena derived from the quantum structure of space-time. The next step would be to study supersymmetric particles in detail and extract crucial clues that could help us understand string theory or whatever deeper theory underlies supersymmetry.

The Tevatron and the LHC accelerate protons — and, in the case of the Tevatron, antiprotons also. Proton accelerators afford the easiest way of reaching the highest possible energy because protons can be accelerated much more easily than other particles.

Unfortunately, proton accelerators have a drawback. They typically produce dozens of uninteresting particles along with the particles of interest. The supersymmetric world is far too complicated to be explored fully at a proton accelerator. For accurate measurements, we need a different kind of machine — one that accelerates electrons and their antiparticles, positrons.

The highest-energy electron accelerators built so far have been at CERN and at the Stanford Linear Accelerator Center in California. These machines have carried out the most precise and complete tests of the standard model of particle physics. In the last decade, the United States, Japan, and Germany have devoted intensive research and development toward a higher-energy electron accelerator known as the Linear Collider, which could reach the energy level needed to study supersymmetric particles.

The yet-to-be-approved Linear Collider, like the LHC, will be a multi-billion dollar project that can be built only with extensive international cooperation — perhaps encouraged by the curiosity of the public in the countries involved.



WHEN A SINGLE ELEMENTARY PARTICLE breaks in two (inset), it occurs at a definite moment in space-time. When a string breaks into two strings (right), different observers will disagree about when and where this occurred. A relativistic observer who considers the dotted line to be a surface of constant time believes the string broke at the space-time point P while another observer who considers the dashed line to be a surface of constant time believes the string broke at Q. *ASTRONOMY:* ROEN KELLY

The astronomy connection

What about those astronomical mysteries we started with? None of the problems yet has any definitive solution, but physicists suspect solutions are linked to the exploration of supersymmetry, string theory, and the quantum nature of space-time.

First, although other possibilities exist, many physicists think galactic dark matter is a cloud of supersymmetric particles gravitationally bound to a galaxy. Calculations show that such a cloud would have just about the right properties. If this supposition proves correct, dark matter will be detected in the next decade. Special underground detectors can spot the rare interactions of dark matter particles passing through Earth. The instruments lie deep underground, often in mines, to screen them from cosmic rays.

Detecting dark matter would be a milestone in astronomy, but not the whole story. Underground detectors would measure the product of the density of dark matter particles times the interaction rate, but that's only a partial solution. To learn how much dark matter of this type exists, scientists would need to measure the interaction rate by producing dark matter particles in accelerators and observing their properties. Thus, the LHC and the Linear Collider, together with supersymmetry, might be key to understanding dark matter.

The dark energy problem is a more difficult challenge. One of the most dramatic discoveries in astronomy and physics in recent years is that the expansion of the universe seems to be accelerating. This points to a tiny but positive energy density of the vacuum (or possibly a more complicated scenario involving another form of dark energy). The vacuum energy is a problem that involves both quantum mechanics, because this energy comes from quantum fluctuations, and gravity, because gravity is the only force in nature that "sees" the energy of the vacuum. Because string theory is the only framework we have for understanding quantum gravity, the vacuum energy poses a problem for string theorists that remains to be solved.

As for inflation, scientists believe it occurred in the early universe at a temperature far above the energy attainable with particle accelerators and relatively close to the energy at which quantum gravity becomes important. We do not yet have a convincing model of how and why inflation transpired because our current models of particle physics are not adequate at the enormous energy levels of inflation. Understanding inflation requires a much better grasp of particle physics than we now have, and possibly a full knowledge of string theory and quantum gravity.

Finally, what was the Big Bang all about, and how could there have been a beginning to space and time? This question certainly involves quantum gravity, because quantum mechanics and general relativity were both important near the Big Bang. That creates another grand challenge for string theorists, even though we do not seem close to an answer. A plausible guess springs from the way quantum gravity and string theory impart a fuzziness to our concepts of space-time. Under ordinary conditions, time seems like a well-defined notion, but as you get closer to the Big Bang, quantum mechanical and stringy fuzziness become more significant. The very notion of time may lose its meaning when one gets back to the beginning — and that, quite likely, will prove to be a key to understanding what the Big Bang really was.