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The Myth Of The Beginning Of Time

String theory suggests that the BIG BANG was not the origin of the universe but simply the outcome of a preexisting state

BY GABRIELE VENEZIANO

The Sciences

Was the big bang really the beginning of time? Or did the universe exist before then? Such a question seemed almost blasphemous only a decade ago. Most cosmologists insisted that it simply made no sense--that to contemplate a time before the big bang was like asking for directions to a place north of the North Pole. But developments in theoretical physics, especially the rise of string theory, have changed their perspective. The pre-bang universe has become the latest frontier of cosmology.

The new willingness to consider what might have happened before the bang is the latest swing of an intellectual pendulum that has rocked back and forth for millennia. In one form or another, the issue of the ultimate beginning has engaged philosophers and theologians in nearly every culture. It is entwined with a grand set of concerns, one famously encapsulated in an 1897 painting by Paul Gauguin: *D'ou venons-nous? Que sommes-nous? Ou allons-nous?* Where do we come from? What are we? Where are we going? The piece depicts the cycle of birth, life and death--origin, identity and destiny for each individual--and these personal concerns connect directly to cosmic ones. We can trace our lineage back through the generations, back through our animal ancestors, to early forms of life and protolife, to the elements synthesized in the primordial universe, to the amorphous energy deposited in space before that. Does our family tree extend forever backward? Or do its roots terminate? Is the cosmos as impermanent as we are?

The ancient Greeks debated the origin of time fiercely. Aristotle, taking the no-beginning side, invoked the principle that out of nothing, nothing comes. If the universe could never have gone from nothingness to somethingness, it must always have existed. For this and other reasons, time must stretch eternally into the past and future. Christian theologians tended to take the opposite point of view. Augustine contended that God exists outside of space and time, able to bring these constructs into existence as surely as he could forge other aspects of our world. When asked, What was God doing *before* he created the world? Augustine answered, Time itself being part of God's creation, there was simply no *before!*

Albert Einstein's general theory of relativity led modern cosmologists to much the same conclusion. The theory holds that space and time are soft, malleable entities. On the largest scales, space is naturally dynamic, expanding or contracting over time, carrying matter like driftwood on the tide. Astronomers confirmed in the 1920s that our universe is currently expanding: distant galaxies move apart from one another. One consequence, as physicists Stephen W. Hawking and Roger Penrose proved in the 1960s, is that time cannot extend back indefinitely. As you play cosmic history backward in time, the galaxies all come together to a single infinitesimal point, known as a singularity--almost as if they were descending into a black hole. Each galaxy or its precursor is squeezed down to zero size. Quantities such as density, temperature and spacetime curvature become infinite. The singularity is the ultimate cataclysm, beyond which our cosmic ancestry cannot extend.

The unavoidable singularity poses serious problems for cosmologists. In particular, it sits uneasily with the high degree of homogeneity and isotropy that the universe exhibits on large scales. For the cosmos to look broadly the same everywhere, some kind of communication had to pass among distant regions of space, coordinating their properties. But the idea of such communication contradicts the old cosmological paradigm.

To be specific, consider what has happened over the 13.7 billion years since the release of the cosmic microwave background radiation. The distance between galaxies has grown by a factor of about 1,000 (because of the expansion), while the radius of the observable universe has grown by the much larger factor of about 100,000 (because light outpaces the expansion). We see parts of the universe today that we could not have seen 13.7 billion years ago. Indeed, this is the first time in cosmic history that light from the most distant galaxies has reached the Milky Way.

Strange Coincidence

NEVERTHELESS, the properties of the Milky Way are basically the same as those of distant galaxies. It is as though you showed up at a party only to find you were wearing exactly the same clothes as a dozen of your closest friends. If just two of you were dressed the same, it might be explained away as coincidence, but a dozen suggests that the partygoers had coordinated their attire in advance. In cosmology, the number is not a dozen but tens of thousands--the number of independent yet statistically identical patches of sky in the microwave background.

One possibility is that all those regions of space were endowed at birth with identical properties--in other words, that the homogeneity is mere coincidence. Physicists, however, have thought about two more natural ways out of the impasse: the early universe was much smaller or much older than in standard cosmology. Either (or both, acting together) would have made intercommunication possible.

The most popular choice follows the first alternative. It postulates that the universe went through a period of accelerating expansion, known as inflation, early in its history. Before this phase, galaxies or their precursors were so closely packed that they could easily coordinate their properties. During inflation, they fell out of contact because light was unable to keep pace with the frenetic expansion. After inflation ended, the expansion began to decelerate, so galaxies gradually came back into one another's view.

Physicists ascribe the inflationary spurt to the potential energy stored in a new quantum field, the inflaton, about 10

^{35} second after the big bang. Potential energy, as opposed to rest mass or kinetic energy, leads to gravitational repulsion. Rather than slowing down the expansion, as the gravitation of ordinary matter would, the inflaton accelerated it. Proposed in 1981, inflation has explained a wide variety of observations with precision [see The Inflationary Universe, by Alan H. Guth and Paul J. Steinhardt; SCIENTIFIC AMERICAN, May 1984; and Four Keys to Cosmology, Special report; SCIENTIFIC AMERICAN, February 2004]. A number of possible theoretical problems remain, though, beginning with the questions of what exactly the inflaton was and what gave it such a huge initial potential energy.

A less widely known way to solve the puzzle follows the second alternative by getting rid of the singularity. If time did not begin at the bang, if a long era preceded the onset of the present cosmic expansion, matter could have had plenty of time to arrange itself smoothly. Therefore, researchers have reexamined the reasoning that led them to infer a singularity.

One of the assumptions--that relativity theory is always valid--is questionable. Close to the putative singularity, quantum effects must have been important, even dominant. Standard relativity takes no account of such effects, so accepting the inevitability of the singularity amounts to trusting the theory beyond reason. To know what really happened, physicists need to subsume relativity in a quantum theory of gravity. The task has occupied theorists from Einstein onward, but progress was almost zero until the mid-1980s.

Evolution of a Revolution

TODAY TWO APPROACHES stand out. One, going by the name of loop quantum gravity, retains Einstein's theory essentially intact but changes the procedure for implementing it in quantum mechanics [see Atoms of Space and Time, by Lee Smolin, on page 82]. Practitioners of loop quantum gravity have taken great strides and achieved deep insights over the past several years. Still, their approach may not be revolutionary enough to resolve the fundamental problems of quantizing gravity. A similar problem faced particle theorists after Enrico Fermi introduced his effective theory of the weak nuclear force in 1934. All efforts to construct a quantum version of Fermi's theory failed miserably. What was needed was not a new technique but the deep modifications brought by the electroweak theory of Sheldon L. Glashow, Steven Wein-berg and Abdus Salam in the late 1960s.

The second approach, which I consider more promising, is string theory--a truly revolutionary modification of Einstein's theory. This article will focus on it, although proponents of loop quantum gravity claim to reach many of the same conclusions.

String theory grew out of a model that I wrote down in 1968 to describe the world of nuclear particles (such as protons and neutrons) and their interactions. Despite much initial excitement, the model failed. It was abandoned several years later in favor of quantum chromodynamics, which describes nuclear particles in terms of more elementary constituents, quarks. Quarks are confined inside a proton or a neutron, as if they were tied together by elastic strings. In retrospect, the original string theory had captured those stringy aspects of the nuclear world. Only later was it revived as a candidate for combining general relativity and quantum theory.

The basic idea is that elementary particles are not pointlike but rather infinitely thin one-dimensional objects, the strings. The large zoo of elementary particles, each with its own characteristic properties, reflects the many possible vibration patterns of a string. How can such a simple-minded theory describe the complicated world of particles and their interactions? The answer can be found in what we may call quantum string magic. Once the rules of quantum mechanics are applied to a vibrating string--just like a miniature violin string, except that the vibrations propagate along it at the speed of light--new properties appear. All have profound implications for particle physics and cosmology.

First, quantum strings have a finite size. Were it not for quantum effects, a violin string could be cut in half, cut in half again and so on all the way down, finally becoming a massless pointlike particle. But the Heisenberg uncertainty principle eventually intrudes and prevents the lightest strings from being sliced smaller than about 10

^{34} meter. This irreducible quantum of length, denoted l_s, is a new constant of nature introduced by string theory side by side with the speed of light, *c*, and Planck's constant, *h*. It plays a crucial role in almost every aspect of string theory, putting a finite limit on quantities that otherwise could become either zero or infinite.

Second, quantum strings may have angular momentum even if they lack mass. In classical physics, angular momentum is a property of an object that rotates with respect to an axis. The formula for angular momentum multiplies together velocity, mass and distance from the axis; hence, a massless object can have no angular momentum. But quantum fluctuations change the situation. A tiny string can acquire up to two units of *h* of angular momentum without gaining any mass. This feature is very welcome because it precisely matches the properties of the carriers of all known fundamental forces, such as the photon (for electromagnetism) and the graviton (for gravity). Historically, angular momentum is what clued in physicists to the quantum-gravitational implications of string theory.

Third, quantum strings demand the existence of extra dimensions of space, in addition to the usual three. Whereas a classical violin string will vibrate no matter what the properties of space and time are, a quantum string is more finicky. The equations describing the vibration become inconsistent unless spacetime either is highly curved (in contradiction with observations) or contains six extra spatial dimensions.

Fourth, physical constants--such as Newton's and Coulomb's constants, which appear in the equations of physics and determine the properties of nature--no longer have arbitrary, fixed values. They occur in string theory as fields, rather like the electromagnetic field, that can adjust their values dynamically. These fields may have taken different values in different cosmological epochs or in remote regions of space, and even today the physical constants may vary by a small amount. Observing any variation would provide an enormous boost to string theory.

One such field, called the dilaton, is the master key to string theory; it determines the overall strength of all interactions. The dilaton fascinates string theorists because its value can be reinterpreted as the size of an extra dimension of space, giving a grand total of 11 spacetime dimensions.

Tying Down the Loose Ends

FINALLY, QUANTUM strings have introduced physicists to some striking new symmetries of nature known as dualities, which alter our intuition for what happens when objects get extremely small. I have already alluded to a form of duality: normally, a short string is lighter than a long one, but if we attempt to squeeze down its size below the fundamental length l_s, the string gets heavier again.

Another form of the symmetry, T-duality, holds that small and large extra dimensions are equivalent. This symmetry arises because strings can move in more complicated ways than pointlike particles can. Consider a closed string (a loop) located on a cylindrically shaped space, whose circular cross section represents one finite extra dimension. Besides vibrating, the string can either turn as a whole around the cylinder or wind around it, one or several times, like a rubber band wrapped around a rolled-up poster [*see box on opposite page*].

The energetic cost of these two states of the string depends on the size of the cylinder. The energy of winding is directly proportional to the cylinder radius: larger cylinders require the string to stretch more as it wraps around, so the windings contain more energy than they would on a smaller cylinder. The energy associated with moving around the circle, on the other hand, is inversely proportional to the radius: larger cylinders allow for longer wavelengths (smaller frequencies), which represent less energy than shorter wavelengths do. If a large cylinder is substituted for a small one, the two states of motion can swap roles. Energies that had been produced by circular motion are instead produced by winding, and vice versa. An outside observer notices only the energy levels, not the origin of those levels. To that observer, the large and small radii are physically equivalent.

Although T-duality is usually described in terms of cylindrical spaces, in which one dimension (the circumference) is finite, a variant of it applies to our ordinary three dimensions, which appear to stretch on indefinitely. One must be careful when talking about the expansion of an infinite space. Its overall size cannot change; it remains infinite. But it can still expand in the sense that bodies embedded within it, such as galaxies, move apart from one another. The crucial variable is not the size of the space as a whole but its scale factor--the factor by which the distance between galaxies changes, manifesting itself as the galactic redshift that astronomers observe. According to T-duality, universes with small scale factors are equivalent to ones with large scale factors. No such symmetry is present in Einstein's equations; it emerges from the unification that string theory embodies, with the dilaton playing a central role.

For years, string theorists thought that T-duality applied only to closed strings, as opposed to open strings, which have loose ends and thus cannot wind. In 1995 Joseph Polchinski of the University of California, Santa

Barbara, realized that T-duality did apply to open strings, provided that the switch between large and small radii was accompanied by a change in the conditions at the end points of the string. Until then, physicists had postulated boundary conditions in which no force acted on the ends of the strings, leaving them free to flap around. Under T-duality, these conditions become so-called Dirichlet boundary conditions, whereby the ends stay put.

All the magic properties of quantum strings point in one direction: strings abhor infinity. They cannot collapse to an infinitesimal point, so they avoid the paradoxes that collapse entails. Their nonzero size and novel symmetries set upper bounds to physical quantities that increase without limit in conventional theories, and they set lower bounds to quantities that decrease. String theorists expect that when one plays the history of the universe backward in time, the curvature of spacetime starts to increase. But instead of going all the way to infinity (at the traditional big bang singularity), it eventually hits a maximum and shrinks once more. Before string theory, physicists were hard-pressed to imagine any mechanism that could so cleanly eliminate the singularity.

Taming the Infinite

CONDITIONS NEAR the zero time of the big bang were so extreme that no one yet knows how to solve the equations. Nevertheless, string theorists have hazarded guesses about the pre-bang universe. Two popular models are floating around.

The first, known as the prebig bang scenario, which my colleagues and I began to develop in 1991, combines T-duality with the better-known symmetry of time reversal, whereby the equations of physics work equally well when applied backward and forward in time. The combination gives rise to new possible cosmologies in which the universe, say, five seconds before the big bang expanded at the same pace as it did five seconds after the bang. But the rate of change of the expansion was opposite at the two instants: if it was decelerating after the bang, it was accelerating before. In short, the big bang may not have been the origin of the universe but simply a violent transition from acceleration to deceleration.

The beauty of this picture is that it automatically incorporates the great insight of standard inflationary theory--namely, that the universe had to undergo a period of acceleration to become so homogeneous and isotropic. In the standard theory, acceleration occurs after the big bang because of an ad hoc inflaton field. In the prebig bang scenario, it occurs before the bang as a natural outcome of the novel symmetries of string theory.

According to the scenario, the pre-bang universe was almost a perfect mirror image of the post-bang one [*see box on page 77*]. If the universe is eternal into the future, its contents thinning to a meager gruel, it is also eternal into the past. Infinitely long ago it was nearly empty, filled only with a tenuous, widely dispersed, chaotic gas of radiation and matter. The forces of nature, controlled by the dilaton field, were so feeble that particles in this gas barely interacted.

As time went on, the forces gained in strength and pulled matter together. Randomly, some regions accumulated matter at the expense of their surroundings. Eventually the density in these regions became so high that black holes started to form. Matter inside those regions was then cut off from the outside, breaking up the universe into disconnected pieces.

Inside a black hole, space and time swap roles. The center of the black hole is not a point in space but an instant in time. As the infalling matter approached the center, it reached higher and higher densities. But when the density, temperature and curvature reached the maximum values allowed by string theory, these quantities bounced and started decreasing. The moment of that reversal is what we call a big bang. The interior of one of those black holes became our universe.

Not surprisingly, such an unconventional scenario has provoked controversy. Andrei Linde of Stanford University has argued that for this scenario to match observations, the black hole that gave rise to our universe would have to have formed with an unusually large size--much larger than the length scale of string theory. An answer to this objection is that the equations predict black holes of all possible sizes. Our universe just happened to form inside a sufficiently large one.

A more serious objection, raised by Thibault Damour of the Institut des Hautes tudes Scientifiques in Bures-sur-Yvette, France, and Marc Henneaux of the Free University of Brussels, is that matter and spacetime would have behaved chaotically near the moment of the bang, in possible contradiction with the observed regularity of the early universe. I have recently proposed that a chaotic state would produce a dense gas of miniature string holes--strings that were so small and massive that they were on the verge of becoming black holes. The behavior of these holes could solve the problem identified by Damour and Henneaux. A similar proposal has been put forward by Thomas Banks of Rutgers University and Willy Fischler of the University of Texas at Austin. Other critiques also exist, and whether they have uncovered a fatal flaw in the scenario remains to be determined.

The other leading model for the universe before the bang is the ekpyrotic (conflagration) scenario. Developed five years ago by a team of cosmologists and string theorists--Justin Khoury of Columbia University, Paul J. Steinhardt of Princeton University, Burt A. Ovrut of the University of Pennsylvania, Nathan Seiberg of the Institute for Advanced Study and Neil Turok of the University of Cambridge--the ekpyrotic scenario relies on the previously mentioned Horava-Witten idea that our universe sits at one end of a higher-dimensional space and a hidden brane sits at the opposite end. The two branes exert an attractive force on each other and occasionally collide, making the extra dimension shrink to zero before growing again. The big bang would correspond to the time of collision [*see box on page 78*].

In a variant of this scenario, the collisions occur cyclically. Two branes might hit, bounce off each other, move apart, pull each other together, hit again, and so on. In between collisions, the branes behave like Silly Putty, expanding as they recede and contracting somewhat as they come back together. During the turnaround, the expansion rate accelerates; indeed, the present accelerating expansion of the universe may augur another collision.

The prebig bang and ekpyrotic scenarios share some common features. Both begin with a large, cold, nearly empty universe, and both share the difficult (and unresolved) problem of making the transition between the pre- and the post-bang phase. Mathematically, the main difference between the scenarios is the behavior of the dilaton field. In the prebig bang, the dilaton begins with a low value--so that the forces of nature are weak--and steadily gains strength. The opposite is true for the ekpyrotic scenario, in which the collision occurs when forces are at their weakest.

The developers of the ekpyrotic theory initially hoped that the weakness of the forces would allow the bounce to be analyzed more easily, but they were still confronted with a difficult high-curvature situation, so the jury is out on whether the scenario truly avoids a singularity. Also, the ekpyrotic scenario must entail very special conditions to solve the usual cosmological puzzles. For instance, the about-to-collide branes must have been almost exactly parallel to one another, or else the collision could not have given rise to a sufficiently homogeneous bang. The cyclic version may be able to take care of this problem, because successive collisions would allow the branes to straighten themselves.

Leaving aside the difficult task of fully justifying these two scenarios mathematically, physicists must ask whether they have any observable physical consequences. At first sight, both scenarios might seem like an exercise not in physics but in metaphysics--interesting ideas that observers could never prove right or wrong. That attitude is too pessimistic. Like the details of the inflationary phase, those of a possible pre-bangian epoch could have observable consequences, especially for the small variations observed in the cosmic microwave background temperature.

First, observations show that the temperature fluctuations were shaped by acoustic waves for several hundred thousand years. The regularity of the fluctuations indicates that the waves were synchronized. Cosmologists have discarded many cosmological models over the years because they failed to account for this synchrony. The inflationary, prebig bang and ekpyrotic scenarios all pass this first test. In these three models, the waves were triggered by quantum processes amplified during the period of accelerating cosmic expansion. The phases of the waves were aligned.

Second, each model predicts a different distribution of the temperature fluctuations with respect to angular size. Observers have found that fluctuations of all sizes have approximately the same amplitude. (Discernible deviations occur only on very small scales, for which the primordial fluctuations have been altered by subsequent processes.)

Inflationary models neatly reproduce this distribution. During inflation, the curvature of space changed relatively slowly, so fluctuations of different sizes were generated under much the same conditions. In both the stringy models, the curvature evolved quickly, increasing the amplitude of small-scale fluctuations, but other processes boosted the large-scale ones, leaving all fluctuations with the same strength. For the ekpyrotic scenario, those other processes involved the extra dimension of space, the one that separated the colliding branes. For the prebig bang scenario, they involved a quantum field, the axion, related to the dilaton. In short, all three models match the data.

Third, temperature variations can arise from two distinct processes in the early universe: fluctuations in the density of matter and rippling caused by gravitational waves. Inflation involves both processes, whereas the prebig bang and ekpyrotic scenarios mostly involve density variations. Gravitational waves of certain sizes would leave a distinctive signature in the polarization of the microwave background [see Echoes from the Big Bang, by Robert R. Caldwell and Marc Kamionkowski; SCIENTIFIC AMERICAN, January 2001]. Future observatories, such as the European Space Agency's Planck satellite, should be able to see that signature, if it exists--providing a nearly definitive test.

A fourth test pertains to the statistics of the fluctuations. In inflation the fluctuations follow a bell-shaped curve, which is known to physicists as a Gaussian. The same may be true in the ekpyrotic case, whereas the prebig bang scenario allows for sizable deviation from Gaussianity.

So, when did time begin? Science does not have a conclusive answer yet, but at least two potentially testable theories plausibly hold that the universe--and therefore time--existed well before the big bang. If either scenario is right, the cosmos has always been in existence and, even if it recollapses one day, will never end.

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GABRIELE VENEZIANO, a theoretical physicist at CERN, was the father of string theory in the late 1960s--an accomplishment for which he received the 2004 Heineman Prize of the American Physical Society and the American Institute of Physics. At the time, the theory was regarded as a failure; it did not achieve its goal of explaining the atomic nucleus, and Veneziano soon shifted his attention to quantum chromodynamics, to which he made major contributions. After string theory made its comeback as a theory of gravity in the 1980s, Veneziano became one of the first physicists to apply it to black holes and cosmology.

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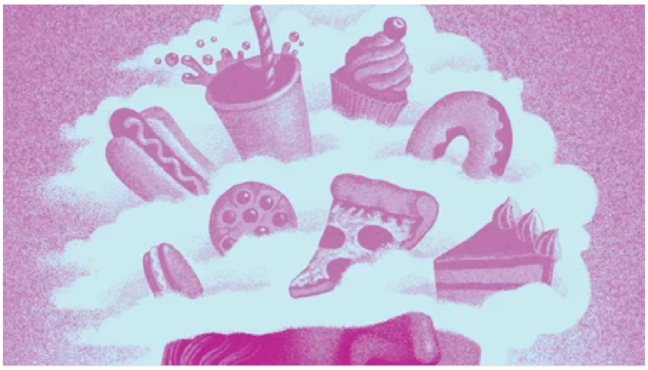

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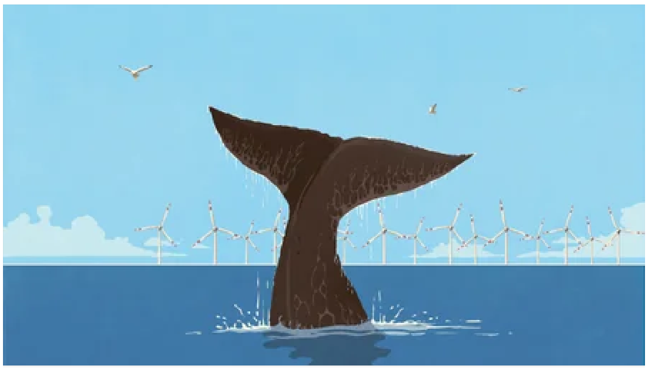

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