# WHERE Did It All Come From?

BY ANTHONY AGUIRRE

Did our universe, and a multitude of others, arise from literally nothing?

OUR OBSERVED UNIVERSE is staggeringly immense and complex. Billions of trillions of stars reside in innumerable galaxies of diverse form and beauty, and these dance in clusters arrayed into filaments hundred of millions of light-years long.

Cosmology — our attempt to understand the universe's origin and evolution — has been the province of mythology and philosophy for millennia. But in the past century it has squarely entered the domain of science, and cosmologists have made great strides in formulating coherent, well-tested, and durable theories describing what astronomers see. These ideas are so successful that we can begin to tackle one of the simplest but most profound questions ever asked: how did it all come to be?

To seek the answer — and even just to ask the question — requires a certain bravado. Let's have some fun and ask an even more audacious version: If you and I had sufficient time, a good set of tools, and a keen knowledge of physics, how would *we* create a universe? How could we manufacture countless billions of galaxies, stars, and planets?

### Cooking up a Cosmos

Fortunately, our task is far easier than it seems. As a first step, we can use cosmologists' hard-won understanding that all of the complexity we see around us arose naturally from an incredibly simple, early state.

Specifically, we have independent, robust lines of evidence that there was a time, about 13.7 billion years ago, when the universe was a billion-degree plasma composed almost entirely of radiation, with only trace amounts of matter. The universe was uniform, except for minuscule density variations, and was expanding so as to double in size every 12 minutes. About 370,000 years later, the universe became transparent to light as it cooled from an ionized plasma into a normal gas, meaning that free electrons combined with protons to form atoms.

Over the ensuing eons, the attraction of the tiny density enhancements gravitationally caused both ordinary matter and more abundant dark matter to collapse into galaxies. As matter was diluted by cosmic

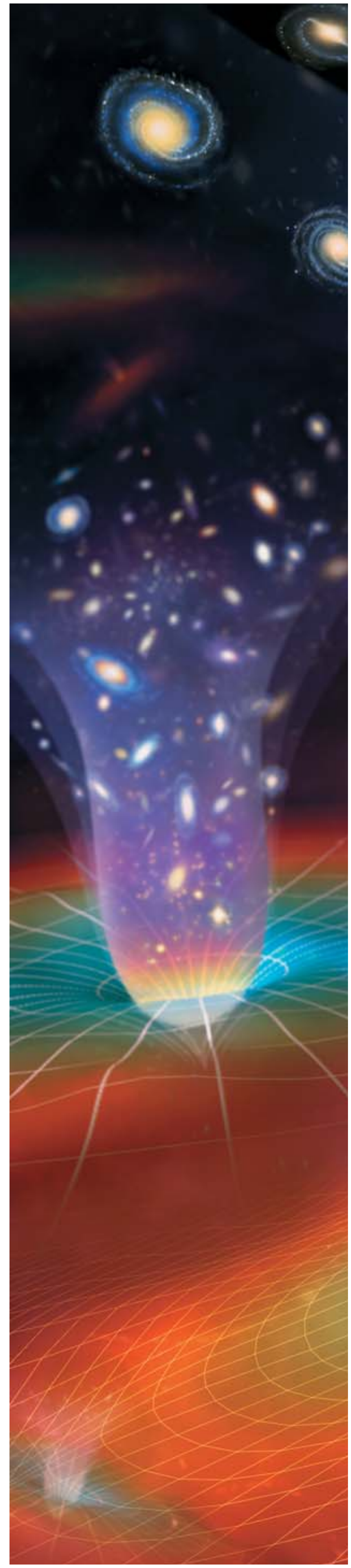
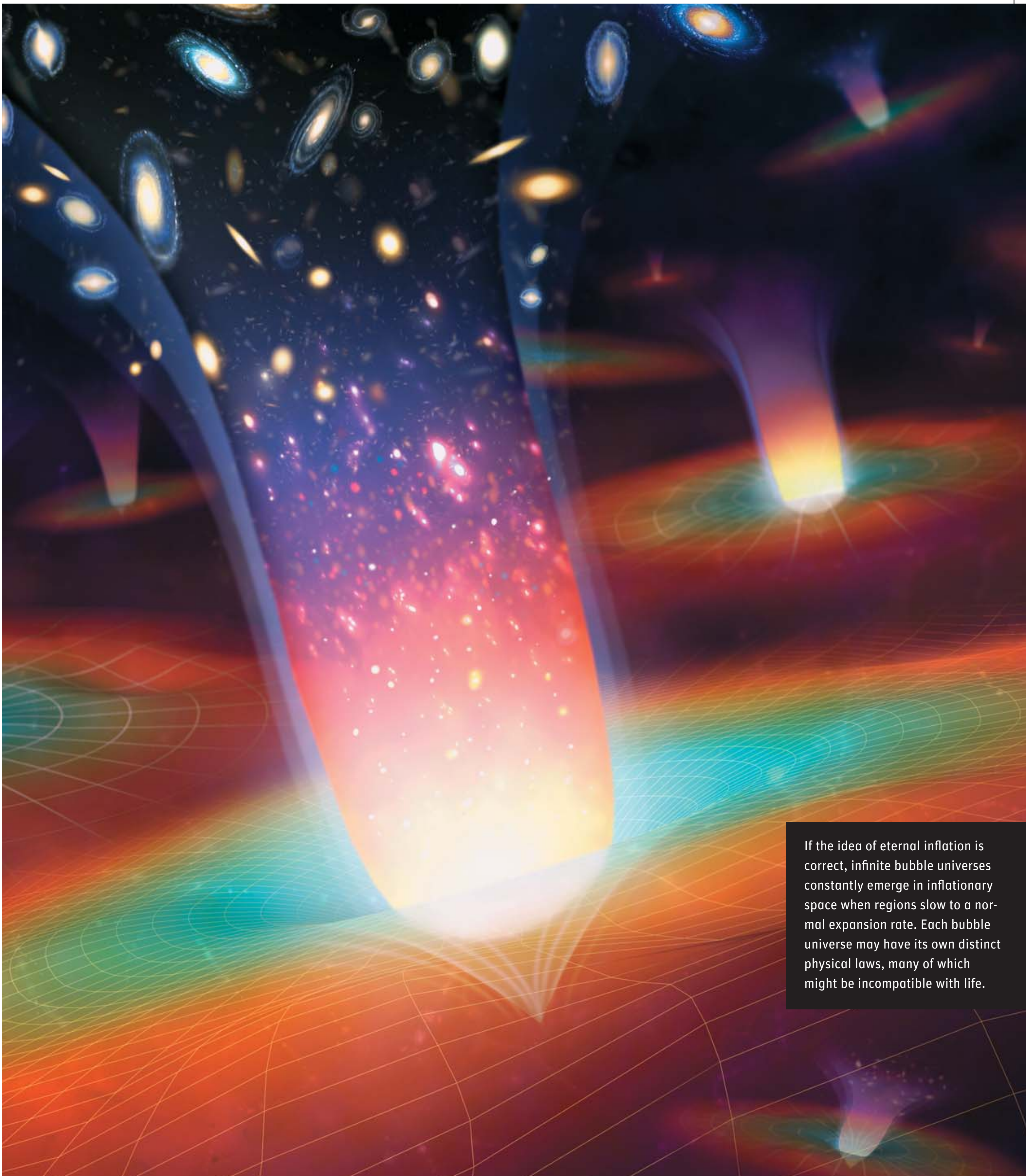
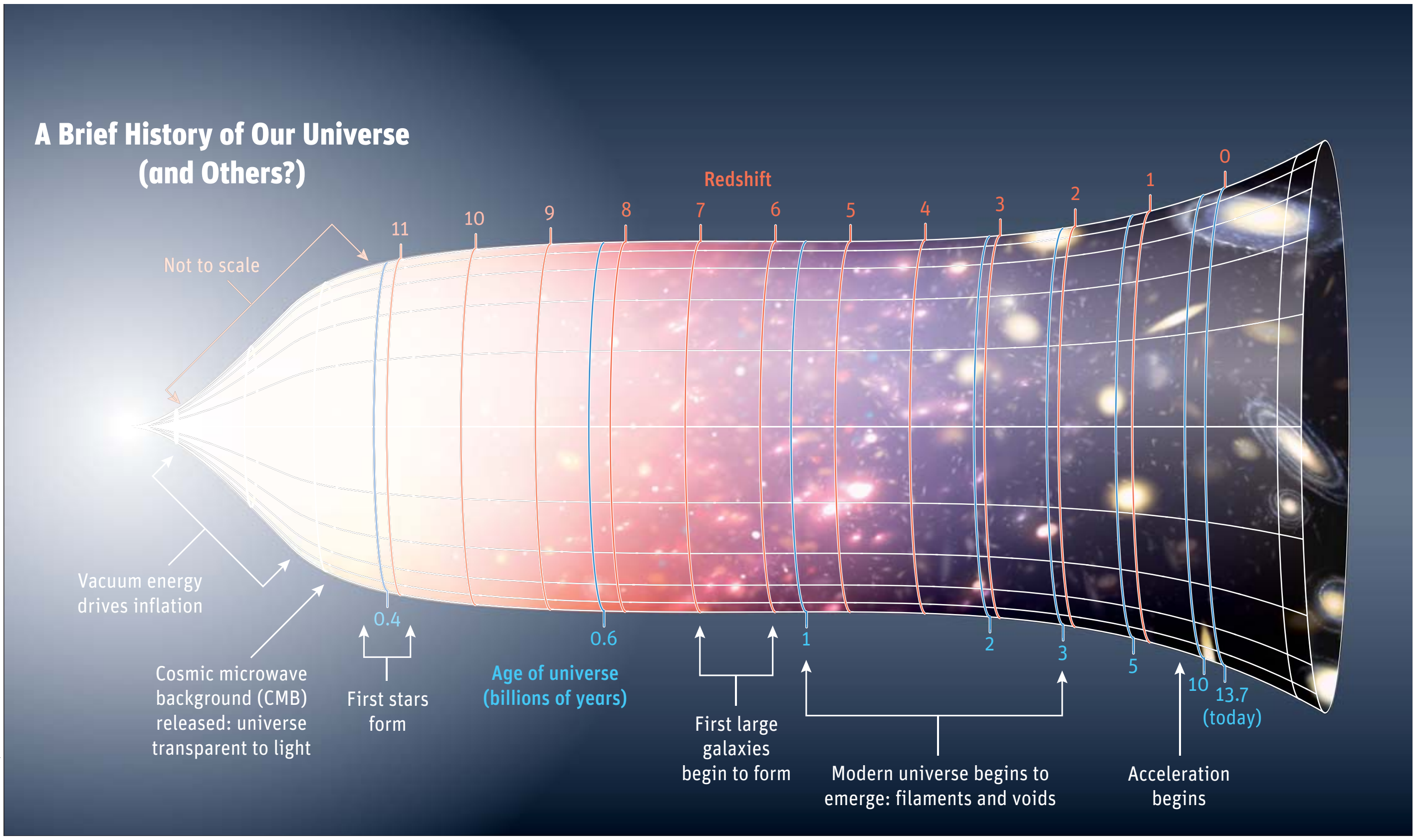


Illustration by Mark Garlick



If the idea of eternal inflation is correct, infinite bubble universes constantly emerge in inflationary space when regions slow to a normal expansion rate. Each bubble universe may have its own distinct physical laws, many of which might be incompatible with life.




MARK GARLICK / *S&T*: CASEY REED

expansion, its influence waned until it gave way to the antigravity pressure of a mysterious dark energy (*S&T*: March 2005, page 32).

Although this picture remains incomplete — we still don't know, for example, what the dark matter and dark energy actually *are* — we have come a long way in our cosmic creation quest. We need only to create a hot, uniform batter of particles and radiation; the laws of physics will take care of the rest.

The theory that the observed universe cooled and evolved from a uniform epoch of, say, a billion degrees, is known as the Big Bang model. Contrary to a common misperception, the Big Bang is not a theory of the universe's beginning, or even of some primordial explosion. It tells us only how the hot batter evolved. But how was the batter made? Here we confront two related conundrums.

First, if we extrapolate the Big Bang model further back in time, just 4 minutes 4 seconds before our billion-degree epoch, the universe's density and temperature appear to have been infinite. Calculations become impossible, and known physics breaks down completely. Uh oh.

Second, where did all this stuff come from? Could all of the universe's contents have been created from nothing? The question is daunting, but let's face it head-on.

### Everything from Nothing?

The idea of creating an entire universe out of nothing sounds absurd because in everyday life we see matter being *conserved.* It may change form, but it is neither created nor destroyed. Physicists have long known that energy is also conserved. Einstein's famous equation $E = mc^2$ showed that mass and energy are interchangeable, so there's really just one law: the conservation of energy.

This law would seem to be an airtight argument against the creation of a universe. If energy is conserved, then the universe — which clearly has scads of mass and energy — could never have come from "nothing," which has none.

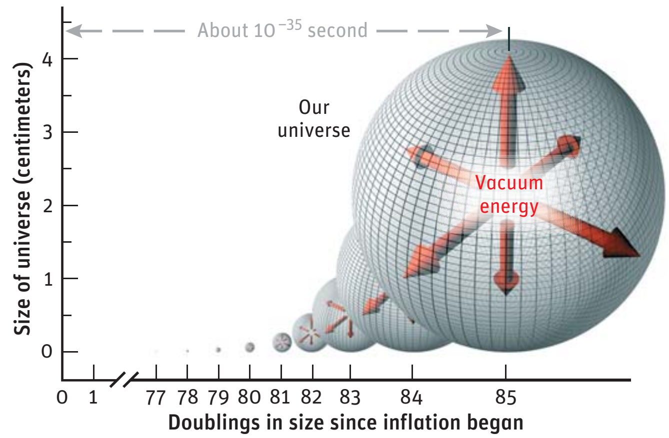
Amazingly, almost every part of that last statement is incorrect. Energy is *not* always conserved, the universe might have begun with *little or no* total energy, and "nothing" *can* have energy! Let's examine these surprising truths in turn.

First, energy and its conservation are not absolute in either Einstein's general theory of relativity, which describes space, time, and the universe's structure as a whole, or in quantum mechanics, the theory of the very small. For example, in general relativity, the energy of a particle such as a photon is conserved only if the geometry of its surrounding space is unchanging (explaining the energy conservation we experience near the relatively static Earth). But because of cosmic expansion, a photon traveling between galaxies loses energy and shifts to longer, redder wavelengths — the redshift of light astronomers see from distant galaxies.

In quantum mechanics, an object's energy can fluctuate over an extremely short time, as exemplified in radioactivity. Although a uranium atom has an energy barrier to breaking apart, a quantum fluctuation can allow a particle to acquire enough energy temporarily to breach this barrier and escape through a process known as *quantum tunneling.*

Second, little or no energy does not imply little or no stuff, because energy can be *negative* as well as positive. For example, gravity provides a negative contribution to the energy of any pair of objects, which becomes more negative as their separation decreases. When a stone falls, it gains kinetic energy (energy of motion), but it also picks up an exactly compensating amount of negative gravitational energy. And because of $E = mc^2$, negative energy is equivalent to negative mass. If you weigh a pair of large rocks on an exceedingly accurate scale, they will weigh slightly less than the sum of the two rocks weighed individually and far apart.

Third, quantum theory predicts that empty space carries *vacuum energy,* as attested experimentally by the Casimir Effect (see the box below). Over the past decade, observations of distant supernovae and the cosmic microwave background have revealed that vacuum energy (or something that behaves quite like it) appears to comprise a shocking three-quarters of the current universe. In Einstein's theory, vacuum energy implies a repulsive, antigravity force. If there is enough vacuum energy to overpower matter's attractive gravity, the universe will expand exponentially — doubling in scale, over and over, in a fixed interval that depends on the amount of vacuum energy. With cosmic acceleration, astronomers observe just this sort of exponential expansion beginning in our universe.

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"Empty" space can carry energy, known as vacuum energy. Many physicists think that a tiny level of vacuum energy constitutes the "dark energy" that is causing cosmic acceleration. In inflation, the same accelerated expansion happened at a vastly higher rate, driven by high-density vacuum energy. Inflation can explain the properties of our universe if it caused the universe to double in scale at least 85 times, after which the vacuum energy transformed itself into matter and radiation, paving the way for galaxies, stars, and planets. At the end of inflation, the observable universe might have been about the size of a golf ball.

**Growing the Universe from a Seed**

These three truths about energy not only undermine the argument against creating a universe from nothing, but also can be combined into a plausible method for cosmic creation. Let's see how.

Imagine a small region of "empty" space, which nonetheless contains vacuum energy. As discussed above, it will expand exponentially, and if there's lots of vacuum energy, it will quickly swell into a stupendous volume of empty — but energetic — space. Is this a violation of energy conservation, or is it a precise, maintained cancellation between positive and negative energy? General relativity does not exactly say, but it does say that the process occurs.

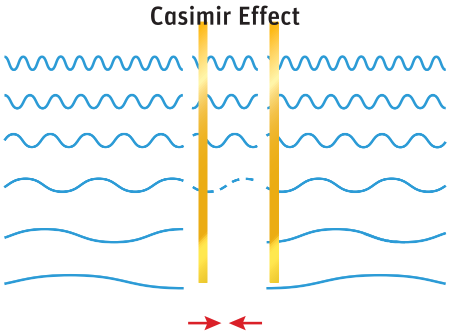
If the vacuum energy is dynamic, meaning it can vary in space and time, it will evolve. It might convert itself into radiation, generating a superhot region that would now expand at a slower rate and cool. Some of this radiation might transform into normal matter, and some into dark matter. Eventually, this fiery mixture would cool and become . . . *just like our universe 13.7 billion years ago.*

Astoundingly, we now have evidence that this very chain of events may have taken place not just in our creation fantasy, but in reality. In the early 1980s, American and Soviet cosmologists developed an idea, called *inflation,* that the universe experienced a very early, very brief epoch of hugely exponential expansion driven by vacuum energy. At that time, most cosmologists thought that the early universe was superhot, superdense, and almost uniform in temperature and density, but they lacked any explanation as to how this special state came into being. This changed when Alan Guth (now at MIT) argued persuasively that a period of inflation would lead to such a state.

But beyond solving the quasi-philosophical problems that motivated it, inflation made two important predictions: the universe's geometry would be flat on very large scales, and the early universe would have density fluctuations of a particular statistical pattern. Both predictions have been born out, most recently and in stunning detail by NASA's

# Defying **Common Sense** by Robert Naeye

**Numerous laboratory experiments have demonstrated conclusively that empty space has energy. For example, quantum mechanics predicts that virtual waves of energy continually form in the vacuum of supposedly "empty space." When two plates are placed close together, waves cannot form between the plates if their wavelengths are longer than the distance between the plates. But shorter waves can form inside and outside the plates. The result is a net force known as the Casimir Effect *(left)* that slowly but inexorably draws the plates closer together.**




**Albert Einstein's general theory of relativity tells us that if you put two rocks together on an exceedingly accurate scale, they will weigh slightly less than if you weigh the same two rocks apart from each other *(right)*. That's because the two rocks have a slight gravitational attraction for each other, which contributes negative energy (and thus negative mass) when the rocks are close together.**

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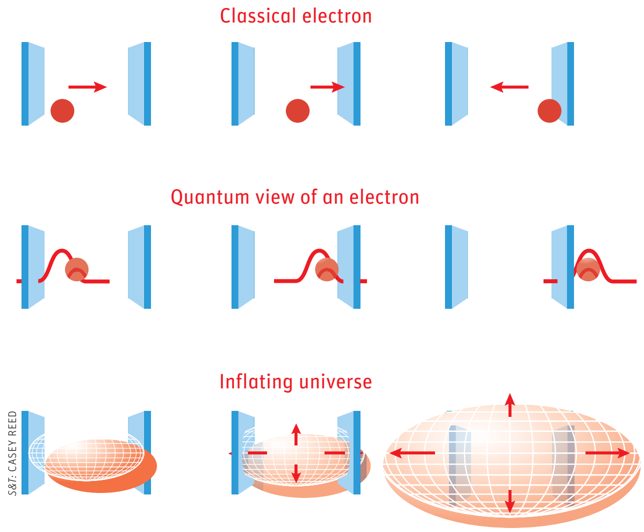
***Senior editor* ROBERT NAEYE *has no common sense, so he understands this perfectly.***




One of the most bizarre phenomena of the microworld is quantum tunneling. In classical physics, a subatomic particle caught between two barriers is predicted to "bounce" back and forth forever. But in quantum theory, a particle's position is described by a probability curve, which can be nonzero even outside a barrier. After a measurement a particle and its probability curve can then lie on the other side. Likewise, our universe may have once been akin to a particle trapped between two barriers. Through quantum tunneling, the universe could have instantly passed through the barriers. Once this happened, vacuum energy could quickly inflate our universe to an enormous size.

Wilkinson Microwave Anisotropy Probe satellite (June issue, page 22). Inflation has passed numerous tests with flying colors, and there are no alternatives anywhere near as compelling. It may actually have happened!

**A Forest of Universes?**

Inflation has profound implications, because its side effects completely change our conception of the universe on enormous scales. We can only observe a region from which light has reached us since inflation ended. But why should inflation have created just this much space and no more? In fact, to explain our *observable* universe, inflation must have also formed *at least* tens or hundreds of similarly sized regions within a much larger volume. The actual number depends on how long inflation lasts. How long is that? Probably forever!

Why? Vacuum energy changes in time and space due to quantum effects, causing inflation to end at different times in different places. In fact, these variations create the density fluctuations from which galaxies formed. Soon after devising the theory, inflation's pioneers — particularly Andrei Linde (now at Stanford University) — realized that on large enough scales, these same fluctuations mean that there will *always* be regions that are still inflating.

In this radical "eternal inflation" scenario, the universe forms a never-ending and ever-expanding sea of space-time, which continually spawns new "bubble universes" where inflation dies out and normal expansion commences. From the inside, one of these could look much like our billion-degree baby universe; it might eventually evolve creatures who would suspect but never observe that infinitely many universes coexist far away in space and time.

But other bubble universes may be quite different. Our best candidate for a theory unifying nature's forces, string theory, yields many — perhaps infinite — versions of post-inflationary physics. In some, the electromagnetic force might be weaker — or stronger. In others, protons or neutrons may have different masses — or they might not exist. Inflation may bring these possibilities into reality through the physical laws of different bubble universes. If these ideas are correct, then the process that created everything we see from just a tiny seed also created much, much more: a true "multiverse" of vast diversity and infinite extent.

This vision, while grand, creates a nightmare for cosmologists. To test a cosmological theory, we must compare our observed universe to a predicted one. But which of the many possible universes should we compare to ours? This problem could be circumvented if we could observe the other bubbles, but they're so far away that we'd have to perform the unattainable feat of traveling faster than light to reach them. All we can do is ask whether our universe is possible (does our theory predict that it exists *somewhere* in the multiverse?), and if it is likely (is it an abundant type of universe?).

**Whence the Seed?**

The ability of vacuum energy to inflate a tiny seed into an infinite number of universes is amazing. But where did that seed come from?

Here we stand on highly speculative ground. Most accounts of what happened before the Big Bang require a theory of *quantum gravity* that combines Einstein's general relativity with quantum mechanics. Physicists still have only limited understanding of quantum gravity, and our best candidate, string theory, so far fails to provide clear answers. But having come this far in our universe-creation quest, we won't turn back here.

One amusing possibility is that a civilization actually created our universe (May issue, page 25). Guth and Edward

## how we know what we know

Do we really know all this cosmic history with such assurance? Indeed, when I first started studying cosmology about 10 years ago, such assertions would have seemed outrageous. But there is good reason to think that we now do.

As just one example, astronomers have *three* independent lines of evidence that between 4.0% and 4.7% of the universe is composed of ordinary matter such as protons and neutrons.

First, they've compared the observed cosmic abundance of deuterium (a hydrogen isotope) to the theoretical predictions of what our billion-degree early universe left as a relic. Second, they've weighed the domi-

Farhi (MIT) first calculated that a suitable inflationary seed has a mass of just a few kilograms. But they found that a seed constructed in the lab would inevitably collapse into a black hole. An inflating seed can be created only by a chance quantum-mechanical process (a subject of my current research) that still holds unsolved mysteries. For example, it's unclear whether the laboratory can be small or whether it must be as large as our universe. Besides, this answer begs another question: where did the laboratory come from?

Another possibility is that the inflationary seed really came from nothing — not empty space, but genuine nothing. Alexander Vilenkin (Tufts University) and his collaborators have described how a tiny noninflating universe can suddenly, via quantum tunneling, become a somewhat larger inflating cosmos. If the size of the initial universe were *exactly* zero, the inflating universe would tunnel from nothing! This process is also not entirely understood. For example, does this nothingness include the laws of physics? How does the universe know when to tunnel if there is no space and time?

A third answer is that the question itself is ill-framed, because it is posed in terms of *nonquantum* gravity and spacetime, whereas in the correct, quantum-gravitational description, concepts such as "space," "time," and even "before" and "after," would only emerge "later" as the universe expanded and became more organized. Pioneered by James Hartle (University of California, Santa Barbara) and Stephen Hawking (Cambridge University, England), this approach is compelling, but bringing it to full fruition would, as with the other approaches, require a deeper understanding of quantum gravity, and work along these lines in string theory is ongoing.

A fourth answer is that there simply was no beginning. If inflation continues forever, why couldn't the universe always have been inflating? As Steven Gratton (Cambridge University) and I worked out, the universe on enormous scales would closely resemble the steady-state cosmological model that was vanquished by the Big Bang. Bubble universes would continually sprout here and there at a steady rate while inflation creates more space in which to fit them. But there would be no beginning; the universe would simply exist eternally.

### How *Did* It All Begin?

In our quest to create a universe — and in cosmologists' parallel quest to explain how ours came to be — we have come a long way. Through a century of research, we understand the universe's basic structure back to when it was a billion-degree, nearly uniform plasma and now strongly suspect that this era was preceded by an early epoch of inflationary expansion. Inflation theory has made a number of testable and correct predictions and also explains how the immense universe that we see around us — and potentially many others — could have arisen from just a tiny seed.


NASA / ESA / STEVEN BECKWITH / HUDF TEAM

It seems inconceivable that our vast universe — and all of its contents — could have arisen from nothing. Yet the attempt to understand how that could have happened is at the forefront of modern cosmology, and scientists are confident that they're closing in on an understanding of how it all came into being.

To watch an interview with the author, look for this month's issue at SkyTonight.com/skytel.

We have plausible but incomplete scientific hypotheses as to how that seed arose — or did not have to arise. We don't know if any of our hypotheses are correct, and the next big advance may drastically change (and yet encompass) our current conception of the universe, just as the Big Bang and inflation theories did in turn.

Cosmologists have therefore yet to answer the question of how it all began. But this question has entered the domain of science. Careful theoretical work combined with a wealth of observations may never give us ultimate answers to how the universe came to be. But they have taken us so far, and the questions are so compelling, that we'd be crazy to give up now. ✴

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**nant form of ordinary matter — intergalactic gas — via direct spectroscopic observations of intergalactic hydrogen. Third, cosmologists have discerned the pattern of temperature fluctuations in the nearly uniform bath of microwave radiation recently measured by NASA's WMAP satellite (June issue, page 22) and this pattern encodes (among other important information) the relative densities of ordinary matter, dark matter, and dark energy.**

**The agreement of all three independent techniques and physical processes is enough to make a cosmologist feel downright smug. Similar complementary and interlocking observations determine the other ingredients of our universe, including dark matter and dark energy (see page 19), leading to a very solid and consistent standard cosmological model. — A. A.**