COSMOLOGY

How the Universe Got Its Bounce Back

By NATALIE WOLCHOVER

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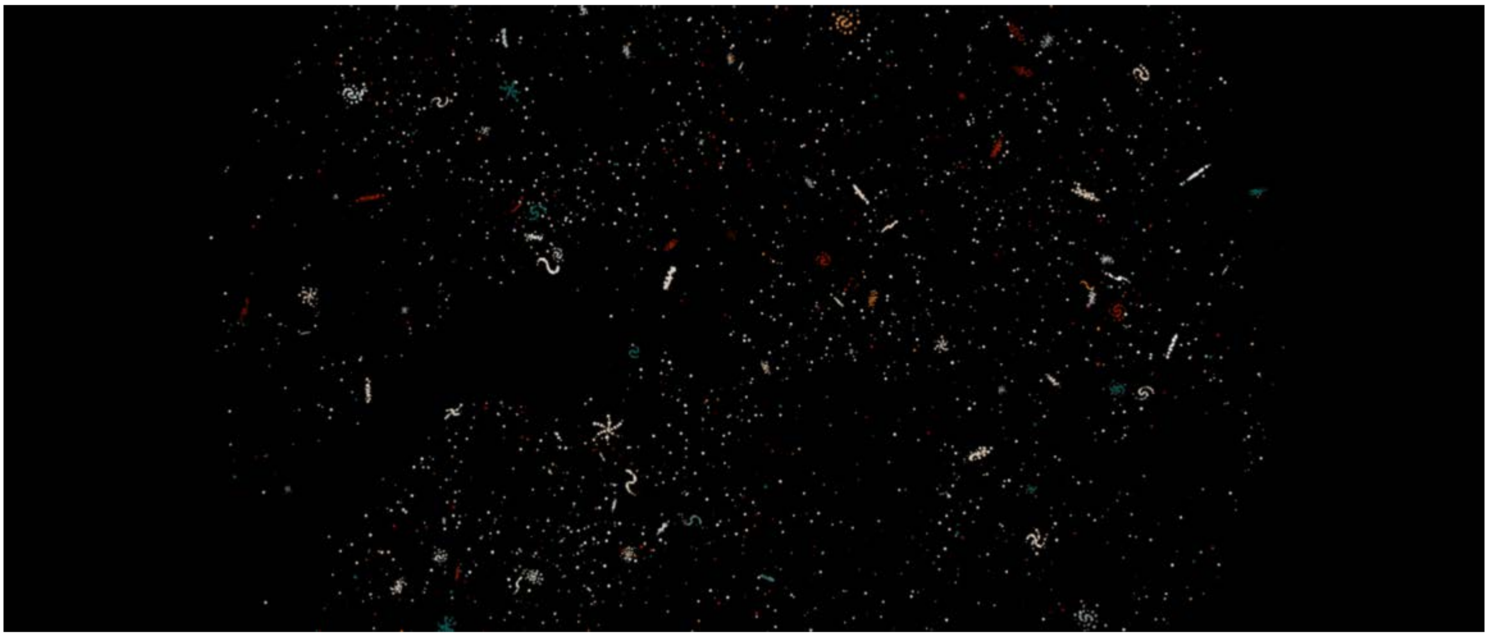
Cosmologists have shown that it's theoretically possible for a contracting universe to bounce and expand. The new work resuscitates an old idea that directly challenges the Big Bang theory of cosmic origins.



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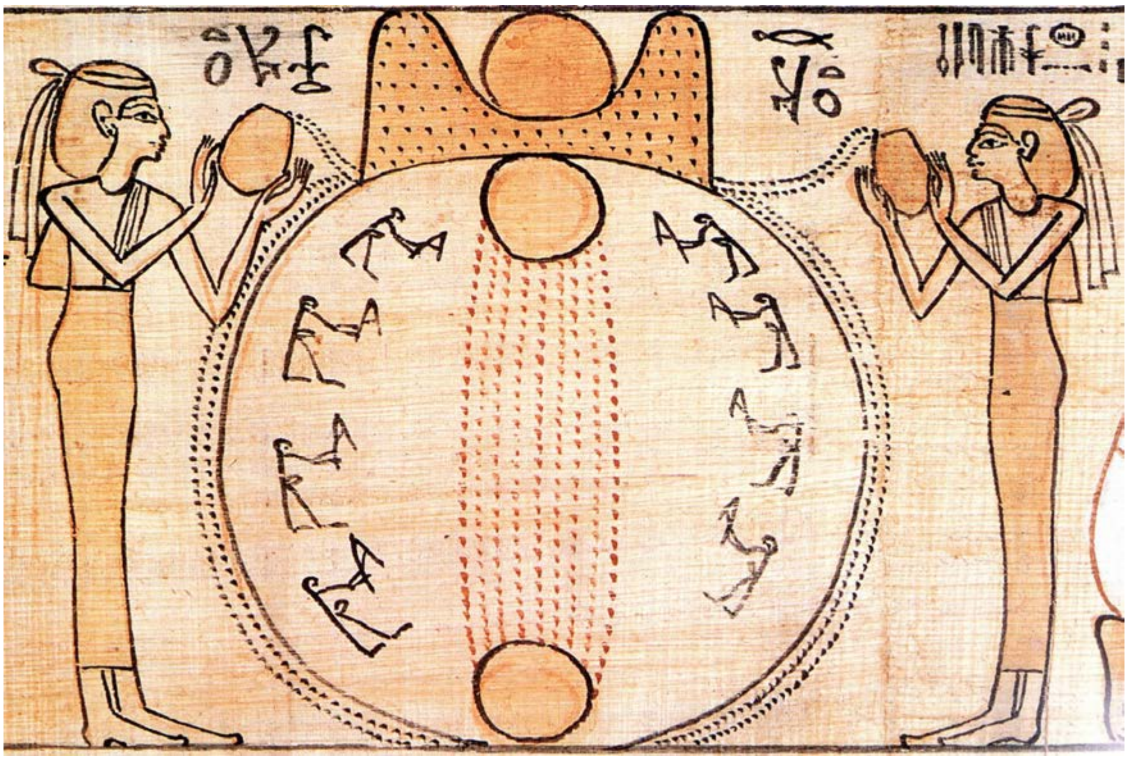
davidope for Quanta Magazine

Humans have always entertained two basic theories about the origin of the universe. "In one of them, the universe emerges in a single instant of creation (as in the Jewish-Christian and the Brazilian Carajás cosmogonies)," the cosmologists Mario Novello and Santiago Perez-Berglia. a noted in 2008. In the other, "the universe is eternal, consisting of an infinite series of cycles (as in the cosmogonies of the Babylonians and Egyptians)." The division in modern cosmology "somehow parallels that of the cosmogonic myths," Novello and Perez-Bergliaffa wrote.

In recent decades, it hasn't seemed like much of a contest. The Big Bang theory, standard stuff of textbooks and television shows, enjoys strong support among today's cosmologists. The rival eternal-universe picture had the edge a century ago, but it lost ground as astronomers observed that the cosmos is expanding and that it was small and simple about 14 billion years ago. In the most popular modern version of the theory, the Big Bang began with an episode called "cosmic inflation" — a burst of exponential expansion during which an infinitesimal speck of space-time ballooned into a smooth, flat, macroscopic cosmos, which expanded more gently thereafter.

With a single initial ingredient (the "inflaton field"), inflationary models reproduce many broad-brush features of the cosmos today. But as an origin story, inflation is lacking; it raises questions about what preceded it and where that initial, inflaton-laden speck came from. Undeterred, many theorists think the inflaton field must fit naturally into a more complete, though still unknown, theory of time's origin.

But in the past few years, a growing number of cosmologists have cautiously revisited the alternative. They say the Big Bang might instead have been a Big Bounce. Some cosmologists favor a picture in which the universe expands and contracts cyclically like a lung, bouncing each time it shrinks to a certain size, while others propose that the cosmos only bounced once — that it had been contracting, before the bounce, since the infinite past, and that it will expand forever after. In either model, time continues into the past and future without end.



Throughout history, origin stories from different cultures have imagined either a moment of creation or a cyclical, eternal universe. Here, Egyptian artwork from around 1000 B.C. depicts the beginning of time.

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Source: Book of the Dead of Khensumose

With modern science, there's hope of settling this ancient debate. In the years ahead, telescopes could find definitive evidence for cosmic inflation. During the primordial growth spurt — if it happened — quantum ripples in the fabric of space-time would have become stretched and later imprinted as subtle swirls in the polarization of ancient light called the cosmic microwave background. Current and future telescope experiments are hunting for these swirls. If they aren't seen in the next couple of decades, this won't entirely disprove inflation (the telltale swirls could simply be too faint to make out), but it will strengthen the case for bounce cosmology, which doesn't predict the swirl pattern.

Already, several groups are making progress at once. Most significantly, in the last year, physicists have come up with two new ways that bounces could conceivably occur. One of the models, described in a paper that will appear in the *Journal of Cosmology and Astroparticle Physics*, comes from Anna Ijjas of Columbia University, extending earlier work with her former adviser, the Princeton professor and high-profile bounce cosmologist Paul Steinhardt. More surprisingly, the other new bounce solution, accepted for publication in *Physical Review D*, was proposed by Peter Graham, David Kaplan and Surjeet Rajendran, a well-known trio of collaborators who mainly focus on particle physics questions and have no previous connection to the bounce cosmology community. It's a noteworthy development in a field that's highly polarized on the bang vs. bounce question.

The question gained renewed significance in 2001, when Steinhardt and three other cosmologists argued that a period of slow contraction in the history of the universe could explain its exceptional smoothness and flatness, as witnessed today, even after a bounce — with no need for a period of inflation.

The universe's impeccable plainness, the fact that no region of sky contains significantly more matter than any other and that space is breathtakingly flat as far as telescopes can see, is a mystery. To match its present uniformity, experts infer that the cosmos, when it was one centimeter across, must have had the same density everywhere to within one part in 100,000. But as it grew from an even smaller size, matter and energy ought to have immediately clumped together and contorted space-time. Why don't our telescopes see a universe wrecked by gravity?

Photo of Anna Ijjas

Anna Ijjas, a theoretical cosmologist at Columbia University.

Olena Shmahalo/Quanta Magazine

"Inflation was motivated by the idea that that was crazy to have to assume the universe came out so smooth and not curved," said the cosmologist Neil Turok, director of the Perimeter Institute for Theoretical Physics in Waterloo, Ontario, and co-author of the 2001 paper on cosmic contraction with Steinhardt, Justin Khoury and Burt Ovrut. In the inflation scenario, the centimeter-size region results from the exponential expansion of a much smaller region — an initial speck measuring no more than a trillionth of a trillionth of a centimeter across. As long as that speck was infused with an inflaton field that was smooth and flat, meaning its energy concentration didn't fluctuate across time or space, the speck would have inflated into a huge, smooth universe like ours. Raman Sundrum, a theoretical physicist at the University of Maryland, said the thing he appreciates about inflation is that "it has a kind of fault tolerance built in." If, during this explosive growth phase, there was a buildup of energy that bent space-time in a certain place, the concentration would have quickly inflated away. "You make small changes against what you see in the data and you see the return to the behavior that the data suggests," Sundrum said.

However, where exactly that infinitesimal speck came from, and why it came out so smooth and flat itself to begin with, no one knows. Theorists have found many possible ways to embed the inflaton field into string theory, a candidate for the underlying quantum theory of gravity. So far, there's no evidence for or against these ideas.

Cosmic inflation also has a controversial consequence. The theory — which was pioneered in the 1980s by Alan Guth, Andrei Linde, Aleksei Starobinsky and (of all people) Steinhardt, almost automatically leads to the hypothesis that our universe is a random bubble in an infinite, frothing multiverse sea. Once inflation starts, calculations suggest that it keeps going forever, only stopping in local pockets that then blossom into bubble universes like ours. The possibility of an eternally inflating multiverse suggests that our particular bubble might never be fully understandable on its own terms, since everything that can possibly happen in a multiverse happens infinitely many times. The subject evokes gut-level disagreement among experts. Many have reconciled themselves to the idea that our universe could be just one of many; Steinhardt calls the multiverse "hogwash."

This sentiment partly motivated his and other researchers' about-face on bounces. "The bouncing models don't have a period of inflation," Turok said. Instead, they add a period of contraction before a Big Bounce to explain our uniform universe. "Just as the gas in the room you're sitting in is completely uniform because the air molecules are banging around and equilibrating," he said, "if the universe was quite big and contracting slowly, that gives plenty of time for the universe to smooth itself out."

Although the first contracting-universe models were convoluted and flawed, many researchers became convinced of the basic idea that slow contraction can explain many features of our expanding universe. "Then the bottleneck became literally the bottleneck — the bounce itself," Steinhardt said. As Ijjas put it, "The bounce has been the showstopper for these scenarios. People would agree that it's very interesting if you can do a contraction phase, but not if you can't get to an expansion phase."

Graphic of the big bang VS cosmic inflation VS the big bound

Lucy Reading-Ikkanda/Quanta Magazine

Bouncing isn't easy. In the 1960s, the British physicists Roger Penrose and Stephen Hawking proved a set of so-called "singularity theorems" showing that, under very general conditions, contracting matter and energy will unavoidably crunch into an immeasurably dense point called a singularity. These theorems make it hard to imagine how a contracting universe in which space-time, matter and energy are all rushing inward could possibly avoid collapsing all the way down to a singularity — a point where Albert Einstein's classical theory of gravity and space-time breaks down and the unknown quantum gravity theory rules. Why shouldn't a contracting universe share the same fate as a massive star, which dies by shrinking to the singular center of a black hole?

Both of the newly proposed bounce models exploit loopholes in the singularity theorems — ones that, for many years, seemed like dead ends. Bounce cosmologists have long recognized that bounces might be possible if the universe contained a substance with negative energy (or other sources of negative pressure), which would counteract gravity and essentially push everything apart. They've been trying to exploit this loophole since the early 2000s, but they always found that adding negative-energy ingredients made their models of the universe unstable, because positive- and negative-energy quantum fluctuations could spontaneously arise together, unchecked, out of the zero-energy vacuum of space. In 2016, the Russian cosmologist Valery Rubakov and colleagues even proved a "no-go" theorem that seemed to rule out a huge class of bounce mechanisms on the grounds that they caused these so-called "ghost" instabilities.

Then Ijjas found a bounce mechanism that evades the no-go theorem. The key ingredient in her model is a simple entity called a "scalar field," which, according to the idea, would have kicked into gear as the universe contracted and energy became highly concentrated. The scalar field would have braided itself into the gravitational field in a way that exerted negative pressure on the universe, reversing the contraction and driving space-time apart —without destabilizing everything. Ijjas' paper "is essentially the best attempt at getting rid of all possible instabilities and making a really stable model with this special type of matter," said Jean-Luc Lehners, a theoretical cosmologist at the Max Planck Institute for Gravitational Physics in Germany who has also worked on bounce proposals.

What's especially interesting about the two new bounce models is that they are "non-singular," meaning the contracting universe bounces and starts expanding again before ever shrinking to a point. These bounces can therefore be fully described by the classical laws of gravity, requiring no speculations about gravity's quantum nature.

From left: Peter Graham of Stanford University, David Kaplan of Johns Hopkins University and Surjeet Rajendran of the University of California, Berkeley.

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Linda A. Cicero/Stanford News Service, Will Kirk/Johns Hopkins University, Sarah Wittmer

Graham, Kaplan and Rajendran, of Stanford University, Johns Hopkins University and the University of California, Berkeley, respectively, reported their non-singular bounce idea on the scientific preprint site arxiv.org in September 2017. They found their way to it after wondering whether a previous contraction phase in the history of the universe could be used to explain the value of the cosmological constant — a mystifyingly tiny number that defines the amount of dark energy infused in the space-time fabric, energy that drives the accelerating expansion of the universe.

In working out the hardest part — the bounce — the trio exploited a second, largely forgotten loophole in the singularity theorems. They took inspiration from a characteristically strange model of the universe proposed by the logician Kurt Gödel in 1949, when he and Einstein were walking companions and colleagues at the Institute for Advanced Study in Princeton, New Jersey. Gödel used the laws of general relativity to construct the theory of a rotating universe, whose spinning keeps it from gravitationally collapsing in much the same way that Earth's orbit prevents it from falling into the sun. Gödel especially liked the fact that his rotating universe permitted "closed timelike curves," essentially loops in time, which raised all sorts of Gödelian riddles. To his dying day, he eagerly awaited evidence that the universe really is rotating in the manner of his model. Researchers now know it isn't; otherwise, the cosmos would exhibit alignments and preferred directions. But Graham and company wondered about small, curled-up spatial dimensions that might exist in space, such as the six extra dimensions postulated by string theory. Could a contracting universe spin in those directions?

Imagine there's just one of these curled-up extra dimensions, a tiny circle found at every point in space. As Graham put it, "At each point in space there's an extra direction you can go in, a fourth spatial direction, but you can only go a tiny little distance and then you come back to where you started." If there are at least three extra compact dimensions, then, as the universe contracts, matter and energy can start spinning inside them, and the dimensions themselves will spin with the matter and energy. The vorticity in the extra dimensions can suddenly initiate a bounce. "All that stuff that would have been crunching into a singularity, because it's spinning in the extra dimensions, it misses — sort of like a gravitational slingshot," Graham said. "All the stuff should have been coming to a single point, but instead it misses and flies back out again."

The paper has attracted attention beyond the usual circle of bounce cosmologists. Sean Carroll, a theoretical physicist at the California Institute of Technology, is skeptical but called the idea "very clever." He said it's important to develop alternatives to the conventional inflation story, if only to see how much better inflation appears by comparison — especially when next-generation telescopes come online in the early 2020s looking for the telltale swirl pattern in the sky caused by inflation. "Even though I think inflation has a good chance of being right, I wish there were more competitors," Carroll said. Sundrum, the Maryland physicist, felt similarly. "There are some questions I consider so important that even if you have only a 5 percent chance of succeeding, you should throw everything you have at it and work on them," he said. "And that's how I feel about this paper."

As Graham, Kaplan and Rajendran explore their bounce and its possible experimental signatures, the next step for Ijjas and Steinhardt, working with Frans Pretorius of Princeton, is to develop computer simulations. (Their collaboration is supported by the Simons Foundation, which also funds *Quanta*

Magazine.) Both bounce mechanisms also need to be integrated into more complete, stable cosmological models that would describe the entire evolutionary history of the universe.

Beyond these non-singular bounce solutions, other researchers are speculating about what kind of bounce might occur when a universe contracts all the way to a singularity — a bounce orchestrated by the unknown quantum laws of gravity, which replace the usual understanding of space and time at extremely high energies. In forthcoming work, Turok and collaborators plan to propose a model in which the universe expands symmetrically into the past and future away from a central, singular bounce. Turok contends that the existence of this two-lobed universe is equivalent to the spontaneous creation of electron-positron pairs, which constantly pop in and out of the vacuum. “Richard Feynman pointed out that you can look at the positron as an electron going backwards in time,” he said. “They’re two particles, but they’re really the same; at a certain moment in time they merge and annihilate.” He added, “The idea is a very, very deep one, and most likely the Big Bang will turn out to be similar, where a universe and its anti-universe were drawn out of nothing, if you like, by the presence of matter.”

It remains to be seen whether this universe/anti-universe bounce model can accommodate all observations of the cosmos, but Turok likes how simple it is. Most cosmological models are far too complicated in his view. The universe “looks extremely ordered and symmetrical and simple,” he said. “That’s very exciting for theorists, because it tells us there may be a simple — even if hard-to-discover — theory waiting to be discovered, which might explain the most paradoxical features of the universe.”

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