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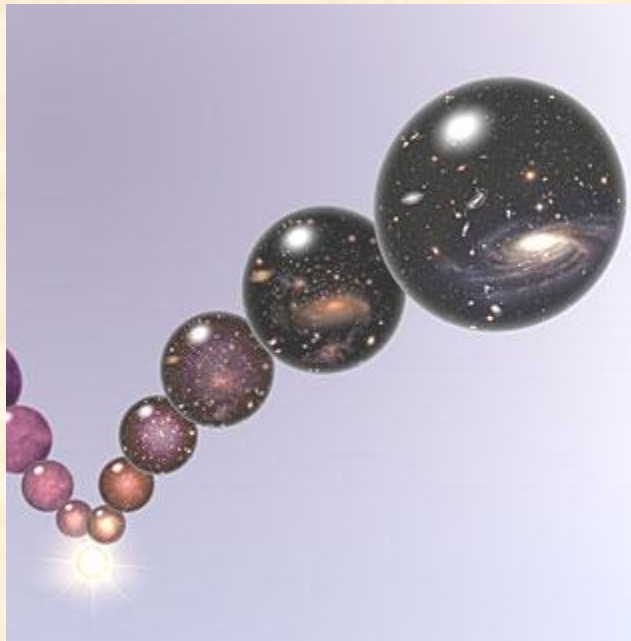
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Big Bang or Big Bounce?: New Theory on the Universe's Birth

by Martin Bojowald / *Scientific American*

Our Universe may have started not with a "Big Bang" but with a "Big Bounce" -- an implosion that triggered an explosion, all driven by exotic quantum-gravitational effects.

Key Concepts



- Einstein's General Theory of Relativity says that the Universe began with the Big Bang singularity -- a moment when all the matter we see was concentrated at a single point of infinite density. But the theory does not capture the fine, quantum structure of spacetime which limits how tightly matter can be concentrated and how strong gravity can become. To figure out what really happened, physicists need a **quantum theory of gravity**.

- According to one candidate for such a theory -- Loop Quantum Gravity -- space is subdivided into "atoms" of volume and has a finite capacity to store matter and energy, thereby preventing true singularities from existing.

- If so, time may have extended before the "Bang". The pre-Bang universe may have undergone a catastrophic implosion that reached a point of maximum density and then reversed. In short, a "Big Crunch" may have led to a "Big Bounce" and then to the "Big Bang".

Atoms are now such a commonplace idea that it is hard to remember how radical they used to seem. When scientists first hypothesized atoms centuries ago, they despaired of ever observing anything so small. Many questioned whether the concept of atoms could even be called "scientific".

Gradually, however, evidence for atoms accumulated and reached a tipping point with Albert Einstein's 1905 analysis of Brownian motion (the random jittering of dust grains in a fluid). Even then, it took another 20 years for physicists to develop a theory explaining atoms (namely Quantum

Mechanics) and another 30 for physicist Erwin Müller to make the first microscope images of them. Today, entire industries are based on the characteristic properties of atomic matter.

Physicists' understanding of the composition of space and time is following a similar path but several steps behind. Just as the behavior of materials indicates that they consist of atoms, the behavior of space and time suggests that they too have some fine-scale structure. Either a mosaic of spacetime "atoms" or some other filigree work.

Material atoms are the smallest indivisible units of chemical compounds. Similarly, the putative space atoms are the smallest indivisible units of distance. They are generally thought to be about 10^{-35} meter in size. Far too tiny to be seen by today's most powerful instruments which probe distances as short as 10^{-18} meter. Consequently, many scientists question whether the concept of atomic spacetime can even be called "scientific". Undeterred, other researchers are coming up with possible ways to detect such atoms indirectly.

The most promising involve observations of the Cosmos. If we imagine rewinding the expansion of the Universe back in time, the [galaxies](#) we see all seem to converge on a single infinitesimal point: the Big Bang singularity. At this point, our current theory of Gravity (i.e., Einstein's General Theory of Relativity) predicts that the Universe had an infinite density and temperature. This moment is sometimes sold as the beginning of the universe -- the birth of matter, space and time.

Such an interpretation, however, goes too far, because the infinite values indicate that General Relativity itself breaks down. To explain what really happened at the Big Bang, physicists must transcend Relativity. We must develop a theory of **Quantum Gravity** which would capture the fine structure of spacetime to which Relativity is blind.

The details of that structure came into play under the dense conditions of the primordial universe. And traces of it may survive in the present-day arrangement of matter and radiation. In short, if spacetime atoms exist, it will not take centuries to find the evidence as it did for material atoms. With some luck, we may know within the coming decade.

Pieces of Space

Physicists have devised several candidate theories of Quantum Gravity, each applying Quantum principles to General Relativity in a distinct way. My work focuses on the theory of **Loop Quantum Gravity** ("loop gravity" for short) which was developed in the 1990s using a 2-step procedure.

First, theorists mathematically reformulated General Relativity to resemble the classical theory of ElectroMagnetism. The eponymous "loops" of the theory are analogues of electric and magnetic field lines. Second, following innovative procedures -- some that are akin to the mathematics of [knots](#) -- they applied quantum principles to the loops. The resulting quantum gravity theory predicts the existence of spacetime atoms [see "[Atoms of Space and Time](#)" by Lee Smolin; *Scientific American*, January 2004].

Other approaches such as string theory and so-called causal dynamical triangulations do not predict spacetime atoms per se but suggest other ways that sufficiently short distances might be indivisible [see "[The Great Cosmic Roller-Coaster Ride](#)" by Cliff Burgess and Fernando Quevedo; *Scientific American*, November 2007 and "[The Self-Organizing Quantum Universe](#)" by Jan Ambjørn, Jerzy Jurkiewicz, and Renate Loll; *Scientific American*, July].

The differences among these theories have given rise to controversy. But to my mind, the theories are not contradictory so much as complementary. String theory, for example, is very useful for a unified

view of particle interactions including Gravity when it is weak. For the purpose of disentangling what happens at the singularity where Gravity is strong, the atomic constructions of Loop Gravity are more useful.

The theory's power is its ability to capture the fluidity of spacetime. Einstein's great insight was that spacetime is no mere stage on which the drama of the Universe unfolds. It is an actor in its own right. It not only determines the motion of bodies within the universe but it also evolves. A complicated interplay between matter and spacetime ensues. **Space can grow and shrink.**

Loop Gravity extends this insight into the quantum realm. It takes our familiar understanding of particles of matter and applies it to the atoms of space and time, providing a unified view of our most basic concepts. For instance, the Quantum Theory of ElectroMagnetism describes a vacuum devoid of particles such as photons. Each increment of energy added to this vacuum generates a new particle.

In the Quantum Theory of Gravity, a vacuum is the absence of spacetime -- an emptiness so thorough we can scarcely imagine it. Loop Gravity describes how each increment of energy added to this vacuum generates a new atom of spacetime.

The spacetime atoms form a dense, ever-shifting mesh. Over large distances, their dynamism gives rise to the evolving universe of classical General Relativity. Under ordinary conditions, we never notice the existence of these spacetime atoms. The mesh spacing is so tight that it looks like a continuum. But when spacetime is packed with energy (as it was at the Big Bang), the fine structure of spacetime becomes a factor and the predictions of Loop Gravity diverge from those of General Relativity.

Attracted to Repulsion

Applying the theory is an extremely complex task. So my colleagues and I use simplified versions that capture the truly essential features of the Universe (such as its size) and ignore details of lesser interest.

We have also had to adapt many of the standard mathematical tools of Physics and cCsmology. For instance, theoretical physicists commonly describe the World using differential equations, which specify the rate of change of physical variables (such as density) at each point in the spacetime continuum.

But when spacetime is "grainy", we instead use so-called difference equations which break up the continuum into discrete intervals. These equations describe how a universe climbs up the ladder of sizes that it is allowed to take as it grows. When I set out to analyze the cosmological implications of Loop Gravity in 1999, most researchers expected that these difference equations would simply reproduce old results in disguise. But unexpected features soon emerged.

Gravity is typically an attractive force. A ball of matter tends to collapse under its own weight. If its mass is sufficiently large, Gravity overpowers all other forces and compresses the ball into a singularity such as the one at the center of a **black hole**. But Loop Gravity suggests that the atomic structure of spacetime changes the nature of Gravity at very high energy densities, making it repulsive.

Imagine space as a sponge and mass and energy as water. The porous sponge can store water but only up to a certain amount. Fully soaked, it can absorb no more and instead repels water. Similarly, an atomic quantum space is porous and has a finite amount of storage space for energy. When energy densities become too large, repulsive forces come into play. The continuous space of General Relativity, in contrast, can store a limitless amount of energy.

Because of the quantum-gravitational change in the balance of forces, no singularity -- no state of infinite density -- can ever arise. According to this model, matter in the early universe had a very high but finite density -- the equivalent of a trillion suns in every proton-size region. At such extremes, Gravity acted as a repulsive force, causing space to expand. As densities moderated, Gravity switched to being the attractive force we all know. Inertia has kept the expansion going to the present day.

In fact, the repulsive gravity caused space to expand at an accelerating rate. Cosmological observations appear to require such an early period of acceleration known as **cosmic inflation**. As the Universe expands, the force driving inflation slowly subsides. Once the acceleration ends, surplus energy is transferred to ordinary matter which begins to fill the universe in a process called "reheating". In current models, inflation is somewhat ad hoc (i.e., added in to conform to observations). But in Loop Quantum Cosmology, it is a natural consequence of the atomic nature of spacetime. Acceleration automatically occurs when the Universe is small and its porous nature still quite significant.

Time before Time

Without a singularity to demarcate the beginning of time, the history of the Universe may extend further back than cosmologists once thought possible. Other physicists have reached a similar conclusion [see "The Myth of the Beginning of Time," by Gabriele Veneziano; *Scientific American*, May 2004]. But only rarely do their models fully resolve the singularity.

Most models (including those from string theory) require assumptions as to what might have happened at this uneasy spot. Loop Gravity, in contrast, is able to trace what took place at the singularity. Loop-based scenarios -- though admittedly simplified -- are founded on general principles and avoid introducing new ad hoc assumptions.

Using the difference equations, we can try to reconstruct the deep Past. One possible scenario is that the initial high-density state arose when a pre-existing universe collapsed under the attractive force of Gravity. The density grew so high that Gravity switched to being repulsive and the Universe started expanding again. Cosmologists refer to this process as a "bounce".

The first "bounce" model investigated thoroughly was an idealized case in which the Universe was highly symmetrical and contained just one type of matter. Particles had no mass and did not interact with one another. Simplified though this model was, understanding it initially required a set of numerical simulations that were completed only in 2006 by Abhay Ashtekar, Tomasz Pawłowski, and Parampreet Singh -- all at Pennsylvania State University.

They considered the propagation of waves representing the Universe both before and after the Big Bang. The model clearly showed that a wave would not blindly follow the classical trajectory into the abyss of a singularity but would stop and turn back once the repulsion of Quantum Gravity set in.

An exciting result of these simulations was that the notorious uncertainty of Quantum Mechanics seemed to remain fairly muted during the Bounce. A wave remained localized throughout the Bounce rather than spreading out as quantum waves usually do. Taken at face value, this result suggested that the Universe before the Bounce was remarkably similar to our own: governed by General Relativity and perhaps filled with stars and galaxies.

If so, we should be able to extrapolate from our Universe back in time (through the Bounce) and deduce what came before, much as we can reconstruct the paths of 2 billiard balls before a collision based on their paths after the collision. We do not need to know each and every atomic-scale detail of the collision.

Unfortunately, my subsequent analysis dashed this hope. The model as well as the quantum waves used in the numerical simulations turned out to be a special case.

In general, I found that waves spread out and that quantum effects were strong enough to be reckoned with. So the Bounce was not a brief push by a repulsive force like the collision of billiard balls. Instead, it may have represented the emergence of our Universe from an almost unfathomable Quantum state -- a world in highly fluctuating turmoil. Even if the pre-existing universe was once very similar to ours, it passed through an extended period during which the density of matter and energy fluctuated strongly and randomly, scrambling everything.

The fluctuations before and after the Big Bang were not strongly related to each other. The Universe before the Big Bang could have been fluctuating very differently than it did afterward and those details did not survive the Bounce. The Universe, in short, has a tragic case of forgetfulness. It may have existed before the Big Bang. But quantum effects during the Bounce wiped out almost all traces of this prehistory.

Some Scraps of Memory

This picture of the Big Bang is subtler than the classical view of the singularity. Whereas General Relativity simply fails at the singularity, Loop Quantum Gravity is able to handle the extreme conditions there. The "Big Bang" is no longer a physical beginning or a mathematical singularity. But it does put a practical limitation on our knowledge. Whatever survives cannot provide a complete view of what came before.

Frustrating as this may be, it might be a conceptual blessing. In physical systems as in daily life, disorder tends to increase. This principle -- known as the Second law of Thermodynamics -- is an argument against an eternal universe. If order has been decreasing for an infinite span of time, the Universe should by now be so disorganized that structures we see in galaxies as well as on Earth would be all but impossible. The right amount of Cosmic forgetfulness may come to the rescue by presenting the young, growing Universe with a clean slate irrespective of all the mess that may have built up before.

According to traditional Thermodynamics, there is no such thing as a truly clean slate. Every system always retains a memory of its past in the configuration of its atoms [see "[The Cosmic Origins of Time's Arrow](#)" by Sean M. Carroll; *Scientific American*, June]. But by allowing the number of spacetime atoms to change, Loop Quantum Gravity allows the universe more freedom to tidy up than Classical Physics would suggest.

All that is not to say that cosmologists have no hope of probing the quantum-gravitational period. **Gravitational waves** and **neutrinos** are especially promising tools because they barely interact with matter and therefore penetrated the primordial plasma with minimal loss. These messengers might well bring us news from a time near to -- or even before -- the Big Bang.

One way to look for gravitational waves is by studying their imprint on the cosmic microwave background radiation [see "Echoes from the Big Bang" by Robert R. Caldwell and Marc Kamionkowski; *Scientific American*, January 2001]. If quantum-gravitational repulsive gravity drove cosmic inflation, these observations might find some hint of it. Theorists must also determine whether this novel source of inflation could reproduce other cosmological measurements. Especially of the early density distribution of matter seen in the cosmic microwave background.

At the same time, astronomers can look for the spacetime analogues of random Brownian motion. For instance, quantum fluctuations of spacetime could affect the propagation of light over long distances. According to Loop Gravity, a light wave cannot be continuous. It must fit on the lattice of space. The smaller the wavelength, the more the lattice distorts it.

In a sense, the spacetime atoms buffet the wave. As a consequence, light of different wavelengths travels at different speeds. Although these differences are tiny, they may add up during a long trip. Distant sources such as gamma-ray bursts offer the best hope of seeing this effect [see “[Window on the Extreme Universe](#)” by William B. Atwood, Peter F. Michelson and Steven Ritz; *Scientific American*, December 2007].

In the case of material atoms, more than 25 centuries elapsed between the first speculative suggestions of atoms by ancient philosophers and Einstein’s analysis of Brownian motion which firmly established atoms as the subject of experimental science. The delay should not be as long for spacetime atoms.

For charts and graphs related to this story, <[click](#)> here .

Note: This article was originally printed with the title "Follow the Bouncing Universe".

About the Author

Martin Bojowald is the leading researcher on the implications of Loop Quantum Gravity for Cosmology. He is a faculty member of the Institute for Gravitation and the Cosmos at Pennsylvania State University.

Bojowald was awarded the First Award of the Gravity Research Foundation Essay Competition in 2003 and the Xanthopoulos Prize of the International Society for General Relativity and Gravitation in 2007.

Outside Physics, he enjoys reading classical literature and long-distance running in the Appalachian Mountains of central Pennsylvania.

Further Reading

[Loop Quantum Cosmology](#)

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Readers' Comments

wagnert at 03:56 PM on 09/17/08

This article would have been timely 15-20 years ago. But the suggestion of a "Big Bounce" seems irrelevant and wrong. The subject of space atoms is current and intriguing, however.

Current information implies that our current Universe will never stop expanding and hence cannot create a future Big Bounce. A previous universe must have had different physical laws that include no negative energy to expand the Universe. This would imply that the Laws of the Universe changed during the bounce. There is no reason to assume that physical laws change between bounces. Thus there was no previous universe.

The quantum superposition on page 51, lower left would appear to be the only reasonable start of our universe. This matches with many other theories relating to the beginning of this Universe.

lagieskes@gmail.com at 08:08 PM on 09/17/08

"bouncing" and "banging" seems to describe movement in black holes

ccubed at 10:51 AM on 09/21/08

Martin Bojowald's article on "Follow the Bouncing Universe" suggests that space/time is quantized. If this is so, what is space/time? How does it expand? Does its size expand as the Universe expands or is space/time continuously created so that the space/time quanta stay the same size? If the latter, where does the new space/time come from? If the former, what is the size of the space/time quanta now?

Saxoman1 at 12:55 AM on 09/22/08

Very interesting. But I don't feel that the explanation for the current movement of our Universe (accelerating expansion) was sufficient IMO. Is this article suggesting that because the Universe is still expanding, it is still "too dense" for gravity to act as an attracting force for matter over long distances? If that is true, then is there a decent guess as to what "dense" for space/time atoms is?

Of course, all this is assuming that the Universe will stop accelerating, will coast, and eventually (but slowly) begin to decelerate until it is at a standstill. Then -- eventually -- begin to "accelerate" in on itself (or collapse). If that is true, we obviously wouldn't be around to witness it. So how can we possibly measure or confirm this given the info we can collect today?

Nonetheless, this article was very interesting.

amazed at 07:13 PM on 09/25/08

I found the idea of a "bouncing" Universe to be appealing even when the author gave no explanation as to how the present acceleration will be stopped for the Universe to re collapse. What is really amazing is the ability of the author to portrait the idea of the "bounce" in Loop Gravity (and the whole field for that matter) as if it was his sole idea. Isn't this a whole research program with many people involved?

materialist at 05:28 PM on 09/27/08

"Bounce" or "Crunch", it's an endless Universe. It had no beginning and was not born or created. It did not arise out of nothing. The standard model of the Big Bang is dead. And good riddance!

Perry at 04:23 PM on 09/28/08

If you have different states of dimensions that flow in different Times (i.e., one is lagging after the other and so on.) Which interact with each other indirectly? If one collapses, the other dimensions will help with the origination of the new one. We can also have different laws governing at different stages and at times have more than one set of Laws working on the same area at the same time.

Remember that we are infants at this new game called Life we are in. We all have much to learn. But we learn. We are all children.

john s. somerset at 08:52 AM on 09/29/08

I too have problems correlating this "loop Quantum Gravity" theory of a bouncing universe with the observed and measured accelerating expansion of the Universe as it is now. The author makes the astounding statement that "... the repulsive gravity caused space to expand at an accelerating rate." Going on, he admits that the period of expansion should have been at an "...early period..." in the formation of the Universe.

Are we still in such a early period that there are still "repulsive" gravity pockets around the Universe? If so, that would seem to require another reversal in known physical laws -- that of the constancy of the effect of Gravity. If every particle of Gravity is repelling every other particle at a force equal to the square of the distance between them (as would be true of a simple reversal in the attractive force), then there shouldn't be pockets where there are gravity particles still too close together to change into an attractive force? The article simply doesn't adequately address these issues.

davidhankinson at 02:06 PM on 09/30/08

I have had implosion-explosion theory for a good while. Can you tell me this problem I have? If you put one balloon inside the other then blow them up then pop the inside one, does it implode or explode or both (depending on what you blow the balloon up with)?

This would explain my expanding-implosion Universe at the same time. One going forward and one going backward

Barzydlo at 09:52 AM on 10/01/08

The following is a direct response to this comment.

I agree. The argument for accelerating expansion is not supported very well. Looks like ad hoc assumptions are being made to fit a loose theory with the annoying facts to make it look like a more tangible cosmology than it really is. There is a much more interesting cosmogony/cosmology at <http://www.collidingstrings.org/strings.htm> called "N-Ice" theory.

N-Ice theory argues that the big bang was more of a "Pop-fizz," and that the accelerating expansion of the Universe indicates the "fizz" part is still going on. That matter is still being introduced into the

universe as it melts from the surface of a sphere of "nuclear ice" formed in a "collapsar" (instead of a classical singularity).

It's a very interesting treatment of a black hole cosmogony that leads to daughter universes. As a bonus, the cosmogony is tied to an independently-developed string theory (Colliding Corpuscular String Theory -- CCST) that also quantizes space, redefines charge and gravity as corpuscular fields, and attributes mass to the recoil of charged particles interacting with the corpuscular couriers of charge and gravity with no Higgs fields required.

In addition, the string theory defines the structures of approximately 30 nuclear shells. I keep hearing how string theory doesn't predict anything. But CCST makes a whole slew of testable predictions. The question is why isn't anyone paying attention to this theory or testing its predictions? It's been around for 30 years. Why hasn't anyone heard of it?

dsanders at 10:31 AM on 10/01/08

I am curious as to what volume the pre-existing universe would have collapsed to before gravity became repulsive.

alphachapmtl at 01:42 PM on 10/03/08

If the Universe is expanding at an accelerating rate, how can it ever bounce back?

lagieskes@gmail.com at 04:32 PM on 10/04/08

At least "bouncing" and "banging" is an attempt to free Gravity from one-dimensional thinking.

Jazz at 05:36 PM on 10/04/08

Regarding the comments of Dr. Wagnert, I am inclined to agree that the idea of periodic "Big Bang" and "Big Crush" giving birth to a "Big Bounce" is a relatively old one. What is important, however, is the mathematics. And as in most articles written for the wider public, there is no mathematics in *Scientific American* publications.

Nevertheless, the idea of space atoms -- unlike what Dr. Wagnert implies -- is not new, either. As I understood from the article of Dr. Ambjorn and Dr. Loll from University of Utrecht, the atoms of space and time are very special kind of atoms which are called (in mathematical jargon) "fractal" or "Cantor" sets.

Again, from what I have read on the other site of Scientific American, the idea of modeling spacetime using these Cantor sets atoms goes back to an Egyptian scientist Mohamed El Naschie. I heard about him only recently. But it would be interesting to see if his theory would support the work of Dr. Martin Bojowald.

It seems a great deal of waste to create whole universes only to destroy them again. If Nature behaved in this way, then It is working according to the principle of maximum inefficiency. In such a universe, Kant should have renamed his monumental work "Critique of Pure Nonsense" rather than "Critique of Pure Reason". But who ever said that our Universe is governed by reason. If you are in any doubt about that, just have a good look at every Head of State on this planet!

Isidore at 04:03 AM on 10/05/08

"Reason" is a purely human invention. The gods (and heads of states) do not believe in it. The only difference is that heads of states usually only destroy but do not create. The Universe is a mandala!

PabloLuis at 07:22 AM on 10/06/08

I am no physicist -- just an architect. So I won't pretend. However, the behavior of physical objects such as concrete structures under very strong pressures such as earthquakes where the nature of the material changes wildly from its state of repose, through its state of being subjected to intense pressure, until it collapses. For then to be rebuilt many years later with a different structure. Will this be a valid metaphor for this kind of transformation?

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