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The Biggest Bang of Them All

Philippe Brieu
University of Michigan

George Musser
Astronomical Society of the Pacific

When did time begin? Where did we come from? What is our destiny? Three very fundamental questions that have always been on human minds.

What was there before the beginning of time? What is there beyond the edge of the universe? Is it possible to travel back in time? Three more bewildering questions that are bound to fascinate youngsters and stump teachers.

Both of us remember asking ourselves these kinds of questions as kids. Unfortunately, nobody around either of us seemed to have the answers. Yet we had to know! We should become astronomers and figure it all out, we thought.

Well, we found out it's not that easy. Scientists have made significant progress in recent years, but plenty of issues remain controversial. This is often illustrated by newspaper headlines: "Scientist sees face of God, confirms Big Bang model" (a reference to results from the Cosmic Background Explorer satellite), "Is the cosmos younger than some of the stars it contains? Cosmology is in chaos" (attempts to measure the expansion rate of the universe), "Astronomers discover billions of new galaxies they did not expect" (Hubble Space Telescope observations), "Physicists describe the grim end of the world" (speculations on the fate of the universe).

All these issues, and many more, make cosmology an exciting field. By definition, cosmology is the study of the universe as a whole, its history, and its overall contents. Cosmology attempts to answer some of the most basic questions we have about the reality we inhabit.

The Lone Universe

Cosmologists are in a unique situation among scientists. There is only one specimen for us to study: the one and only universe we live in. We cannot reproduce it; we cannot take another one and see what happens to it; we cannot compare it to anything else, as astronomers routinely do with planets, stars, and galaxies. Nor can we experiment with what we are studying. We can only observe it passively.

Moreover, we are inside the universe (by definition). That makes it even more difficult to study. Cosmologists are like dentists trying to operate on their own teeth. We are trapped inside the object of our study. In science, it always helps to look at things from the outside. Zoologists try not to be seen by the animals they study, in order not to influence their behavior. Meteorologists look at storm systems from above using weather satellites. But we cannot escape from the universe. We cannot go outside it and take a look.

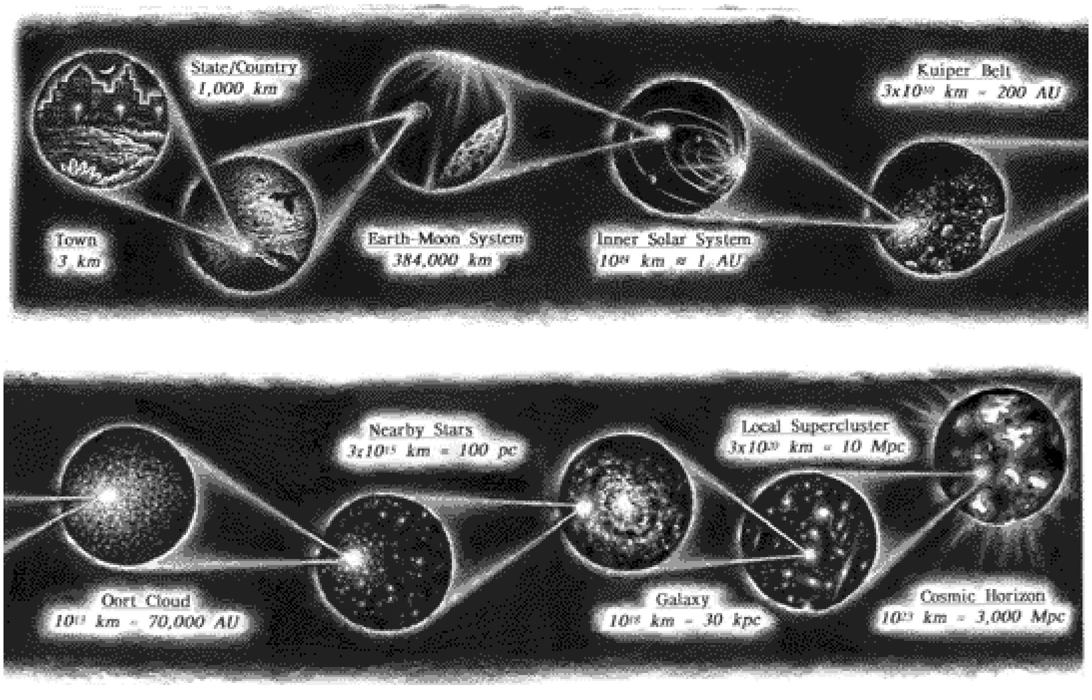
This means that we have to be careful about the meaning we give to what we see nearby and far away. If you look around you, you can probably see a wall, a door, a window, a closet. If you look farther away, you can see a street, other buildings, maybe mountains in the distance. In between could be a farm, a lake, a forest, a highway. So you can see very different things in different directions and at different distances.

If you could keep looking farther away, you would eventually see the ocean. At that point, you could talk in terms of land vs. water: here a continent, there an ocean, another continent, and so on. Someone else could do the same from anywhere on Earth, and while his or her immediate neighborhood could be quite different from yours, on a large enough scale that of the whole Earth the two of you would have the same basic description: land vs. water.

In cosmology, galaxies are the land and the space between galaxies is the water. It is only on the scales of galaxies and larger groupings that we can talk about the universe in general. On that scale, your exact position in the universe does not matter, because it looks roughly the same from any location in any direction: galaxies all.

This observation is the starting point of cosmology. Just as Earth is not the center of the solar system, it is not the center of the universe, but rather some random location equivalent to any other location. In technical terms, cosmologists say the universe is "homogeneous" and "isotropic" on its largest scales. Homogeneous means that the universe has the same basic composition and structure everywhere. Isotropic means that it looks basically the same in every direction.

Cosmologists also expect that the same laws of physics gravity, motion, electricity and magnetism, and so on apply everywhere at all times. This, too, is supported by observations. If the laws varied even slightly, distant stars would refuse to shine, orbits would go haywire, light would look sickly. We see none of this. The remarkable uniformity of the universe is what allows us to study it in its entirety.



How big is the universe, anyway? Each of these bubbles is about 300 times as wide as the previous one. If you start with your hometown and zoom out nine times, you reach the edge of the observable universe. This diagram is a simple example of a logarithmic scale. Incidentally, if you went the other direction, shrinking each bubble by a factor of 300, you would end up with a speck smaller than the smallest known subatomic particle. So, human beings are at the middle of the range of cosmic scales. We are about as small in comparison to the universe as subatomic particles are in comparison to us. Diagram by Kathleen L. Blakeslee for the ASP.

The Biggest Bang of Them All

The Mother of All Bangs

Armed with these assumptions, observations, and laws, cosmologists try to build a theory of the development, or evolution, of the universe. Did it always exist or was it born? If it was born, how? What will happen to it in the future?

Can science even hope to answer these questions? Most cosmologists think so. Over the past 70 years, they have constructed and tested a theory that seems to explain the major properties of the universe: the Big Bang theory. The theory is based on Albert Einstein's general theory of relativity, one of the advances in physics during the early part of the century which provided the intellectual basis for modern cosmology.

Einstein's theory involves equations that scientists can solve to describe the evolution of the universe. One of the possible solutions indicates that the universe was born. At the instant of birth, everything was concentrated in one tiny point and that means everything: all the matter, all the radiation, all the energy we see today. Not surprisingly, the temperature at that point was extremely high. The universe started to expand rapidly, scattering its contents equally in all directions over larger and larger distances. Because this sounds a lot like an explosion, it has been dubbed the Big Bang.

The theory has two basic ideas: The universe started out infinitely small and hot several billion years ago, and it has been expanding and cooling ever since. But the theory does not say what caused this expansion. It does not say how stars and galaxies formed. And it does not predict how much matter the universe contains or what form it is in.

This is an important point: The Big Bang theory allows for many different scenarios of the detailed evolution and composition of the universe. It is simply the foundation on which specific cosmological models are built. You could compare it to making vegetable soup. You know what you have to do: cook vegetables, crush them, add water, and warm up the whole thing. But different people use different vegetables, or different amounts of water, or different cooking times. They end up with soups that taste different, but more or less match the one pictured in their cookbook.

Similarly, cosmologists use different recipes based on the Big Bang. They adjust their equations to create models of the universe, which they then compare to what they see in their guidebook: the sky. If the comparison fails, it does not mean that the whole Big Bang theory is wrong merely that they did not use the correct recipe, in which case they must change their recipe and see whether the new one tastes any better. Cosmologists may argue about their specific models, but few these days question the Big Bang itself.

For the Big Bang to be proved wrong, astronomers would have to observe a phenomenon that contradicts one of the truly basic ideas. That would happen if, for example, the distribution of galaxies were found not to be homogeneous, or if a star were confirmed to be older than the universe. Such problems have been raised, but never confirmed. Over the years, the three key pieces of evidence for the Big Bang have only grown more compelling. One explains how the chemical elements were created; one explains how fast the universe is growing; and one lets us see the bang itself.

How to Make an Element

It is sometimes said that we are children of the stars. Most of the chemical elements in our bodies, such as carbon and oxygen, did not exist early on in the universe. They were created much later by stars. How do we know this? Because of a theory called nucleosynthesis.

Nucleosynthesis describes how the cores of atoms (nuclei) are formed (synthesized) in the universe. There are two types of nucleosynthesis. One took place very early in the history of the universe (during the first three minutes) and is therefore called primordial nucleosynthesis. The other type, stellar nucleosynthesis, is an ongoing process inside stars such as our Sun.

It was the theory of primordial nucleosynthesis that first put the Big Bang theory on solid footing. Primordial nucleosynthesis is a merger of Big Bang theory and high-energy particle physics. The Big Bang theory tells us the conditions that existed in the early universe and how those conditions changed with time. Particle accelerators can reproduce those conditions, or at least come close. It turns out that certain nuclear reactions occurred at different stages in the evolution of the universe.

Initially the universe was a dense soup of the most elementary subatomic particles, known as quarks. There were no atomic nuclei yet, not even the building blocks of nuclei, protons and neutrons. As the universe cooled down, the quarks clumped together to form protons and neutrons. Because the proton is the only component of the nucleus of the hydrogen atom, hydrogen was the first element created in the universe. Later nuclear reactions mixed protons and neutrons, producing helium and a smidgen of lithium.

These were the three primordial elements, and they are the lightest in the periodic table. When you drink a glass of water, you are swallowing hydrogen atoms that are as old as the universe itself. In addition, primordial nucleosynthesis produced a fourth atomic nucleus: deuterium, a form of hydrogen which contains a neutron in addition to the proton.

All the other elements from beryllium to uranium did not exist until a few billion years later, when stars got into the nucleosynthesis act. Stars do not produce any deuterium, but they do create some additional helium by burning hydrogen. This means that all the deuterium and most of the helium we see today comes from the birth of the universe.

The theory makes specific predictions for the amount of the elements we should see in the universe. Moreover, the theory predicts those amounts for all the elements at once, whereas the observations for each element are independent. If all the observed amounts agreed with theory except for one, the whole theory would have to be rejected. Yet all those independent measurements agree a very strong case that the theory is correct.

You can think of this as a mini jigsaw puzzle. If you make even one mistake as you assemble the puzzle, you will end up with at least one piece that does not fit, and you'll have to start all over again. Conversely, if all the pieces fit together and none are left over, you can be pretty confident that you got it right. Here, the pieces are the measurements of element abundances. They all fit together.

What do cosmologists mean by "the universe"? Obviously, the universe consists of everything there is. But to study "everything" would be far too complicated, so cosmologists study the universe as a unit just as a doctor studies your body as a unit without thinking about all the atoms inside it.

If you stand on a hill and look out at the view, you can see things at various distances: grass, trees, buildings, planets, stars, galaxies. By drawing your attention to different distances, you can place things into groups and treat each group as a single unit: lawn, forest, city, solar system, galaxy, cluster of galaxies. The clusters of galaxies comprise the largest unit of all: the universe. The most distant clusters are so far away than it has taken almost the age of the universe for their light to reach us. Diagram by Kathleen L. Blakeslee for the ASP.

The Biggest Bang of Them All

The Growing Universe

The second piece of evidence for the Big Bang is the observed expansion of the universe. The American astronomer Edwin Hubble became world famous for measuring it in the 1920s. He noticed that almost all the galaxies are moving away from us and are moving faster the farther away they are. He established that the velocity (v) of a galaxy is proportional to its distance (d) from us: $v = H \times d$, where H is a number known today as the Hubble constant. This equation is now known as Hubble's law and the so-called Hubble constant is really constant only in space; it varies through time.

To visualize what Hubble's law means, take a balloon and draw some dots on it. As you inflate it, you can see that the distance between every pair of dots increases. Let out the air, catch your breath, and repeat the experiment. Imagine that you are one of the dots looking at the other dots. From the dot's point of view, the other dots all seem to be getting farther away, like ships sailing from a harbor in different directions. It doesn't matter which dot you pick; each dot sees the same thing.

Based on this simple analogy, scientists deduced that Hubble's law is exactly what you'd expect if the universe were expanding. Galaxies in the expanding universe are like dots on the inflating balloon, or ships in an immense ocean that keeps getting bigger with time.

Of course, things are a little different in the real universe. We are not on the (two-dimensional) surface of a balloon. It is our three-dimensional universe that is expanding. We cannot see it from the outside, as in the case of the balloon. This is a perfect example of how our inability to escape the universe limits our view. Sometimes it is impossible for us to visualize what is going on, and scientists are reduced to talking in purely mathematical terms.

The Hubble constant is one of most important numbers in cosmology. Going back to Hubble's law, you can see that the constant is velocity divided by distance. Since velocity itself is distance divided by time, the inverse of the Hubble constant is simply time. This time, it turns out, is the approximate age of the universe.

To understand this, imagine that you and your brother want to visit some relatives. You both leave the house at the same time, but he drives 120 miles north to your grandmother's and you drive 120 miles south to your uncle's. Both of you go an average velocity of 60 mph. When you arrive, your uncle asks how long the drive took, but let's suppose you forgot when you left. Knowing the distance and the speed, you calculate that you drove for 120 miles divided by 60 mph, or 2 hours. Your brother makes the same calculation and reaches the same conclusion. Relative to each other, you drove 240 miles at 120 mph, which again implies a 2-hour journey.

This situation is analogous to Hubble law's. Astronomers can estimate how fast our Milky Way galaxy and, say, the galaxy M100 are traveling away from each other, as well as the distance between them. By dividing distance by velocity, they deduce the time in the past when the two must have departed from the same point. You can do this for any pair of galaxies, and Hubble's law will imply that all left the same point at the same time the very essence of what we call the Big Bang.

Until a couple of years ago, the Hubble constant was only known to within a factor of two, and a fierce debate was raging about its value. But thanks in large part to Hubble Space Telescope observations, the constant is now thought to be between 60 and 70 kilometers per second per megaparsec, implying an age of about 14 billion years. The oldest known star is also about 14 billion years old.

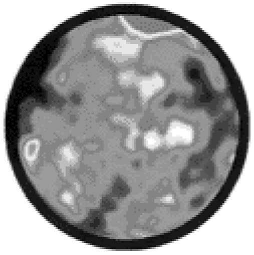
Some other measurements of the Hubble constant have implied an age of about 10 billion years, which, if true, might call the whole Big Bang theory into question. Those measurements have caused a media hoopla these past few years, even though astronomers have known of a potential problem for decades. In fact, some earlier estimates implied an even younger universe! But the precise conversion from Hubble constant to age is not as simple as dividing distance by velocity. Other effects could cause the universe to be older than the constant implies, just as, in the previous example, the road trip could have taken more than 2 hours if you had stopped for coffee. The observations now seem to be settling on a value that is fully consistent with the Big Bang theory.

In the Beginning

Of course, an easier way to prove the Big Bang would be to look back all the way to the beginning of time and watch the universe unfold. Because light travels at a finite speed, any object we see today is actually what it was when it emitted the light. So, the farther away we look, the further back in time we see. We see the Moon as it was a second ago, the Sun as it was 8 minutes ago, the Andromeda galaxy as it was 2 million years ago. Why not look all the way back?

Unfortunately, this is not possible. In its formative years, the universe was too hot and dense for light to get through. It was filled with light, but also with electrons, which shoved the light particles around and kept them confined. Space was opaque. Until, that is, about 300,000 years after the Big Bang began.

At that time, the atomic nuclei grabbed the electrons and put an end to their horseplay. At last, all those photons were able to escape. They streamed off in every direction, like the flash of a bomb. The Big Bang theory says that we should see this flash in the form of a light that seems to be coming from all around us. This is the closest we can get to actually seeing the Big Bang happen. It is our cosmic horizon; we cannot see through it or beyond it.



The primordial glow. An explosion produces a bright flash, right? Well, the Big Bang produced a bright flash, too known as the "cosmic background radiation." Since we are inside the universe, we are inside the Big Bang, and so the bright flash is all around us. We can't see it with our eyes because the Big Bang occurred so long ago that the flash has dimmed. But it can still be seen by radio telescopes and, in fact, causes interference with satellite communications. The flash was produced at the time the universe became transparent, 300,000 years after the Big Bang started. For the most part, the flash is quite uniform. But when you amplify it 100,000 times, you can see bright and dark patches. These patches represent clumps of matter which later became clusters of galaxies. Image courtesy of Charles L. Bennett, NASA Goddard Space Flight Center.

Fortunately, the flash is not as intense as it was billions of years ago. The expansion of the universe has stretched the wavelength of the light and sapped its energy. In fact, the wavelength has been stretched so much that the light has turned into microwave radiation.

The discovery of this radiation in 1965 was the ultimate triumph of the Big Bang theory. No other theory could account for it. Since 1989, the Cosmic Microwave Background satellite has been measuring the radiation and found that it looks almost exactly the same in all directions: It is isotropic, just as the Big Bang theory predicts.

The satellite did find that the radiation varies by a few parts in a million across the sky, which means that the universe had developed a slight unevenness by the time it set free the light. Far from disproving the Big Bang, this unevenness was a victory for models of galaxy formation based on the theory. After all, at small scales, the universe is not homogeneous. There are galaxies, planets, toadstools. At some point, the utterly smooth early universe had to start developing lumps seeds that could grow into the intricate structures we see today. The unevenness in the radiation represents those lumps. Some even speculate that the unevenness could also reflect whatever processes produced the Big Bang to begin with; one cosmologist has exclaimed we are seeing "the face of God," a fossil of creation.

At this point, the line between science and religion or philosophy becomes blurred. This isn't too surprising, since cosmology is attempting to answer some of the most fundamental questions we can ever have.

We have been able to use science to find out when time began, where we come from, and what our destiny could be. But we cannot yet say what there was before time began or what there is beyond the universe. The universe we live in is the only one we can reach by observation, and the known laws of physics cannot be extended to a hypothetical time before the Big Bang. Those are philosophical and theological issues that science cannot and does not deal with.

The Big Bang theory does say that the universe had a beginning and that it may have an end. Other theories, such as the steady-state theory, held that the universe was eternal, but this turned out to be incompatible with observations. Someday the Big Bang theory, too, may be replaced with a better, more comprehensive theory. Maybe that theory will answer the questions about "beyond" and "before." But even if the Big Bang theory is not the final answer, it is the only scientific theory that can accommodate everything we currently know about the universe.

PHILIPPE BRIEU is a research investigator at the University of Michigan in Ann Arbor. He uses supercomputers to figure out how structures in the universe formed. His email address is philippe@astro.physics.lsa.umich.edu.

GEORGE MUSSER is the editor of *Mercury* magazine.

The Fate of the Universe

Cosmologists aren’t just concerned with the history of the universe. They can also make educated guesses about its future.

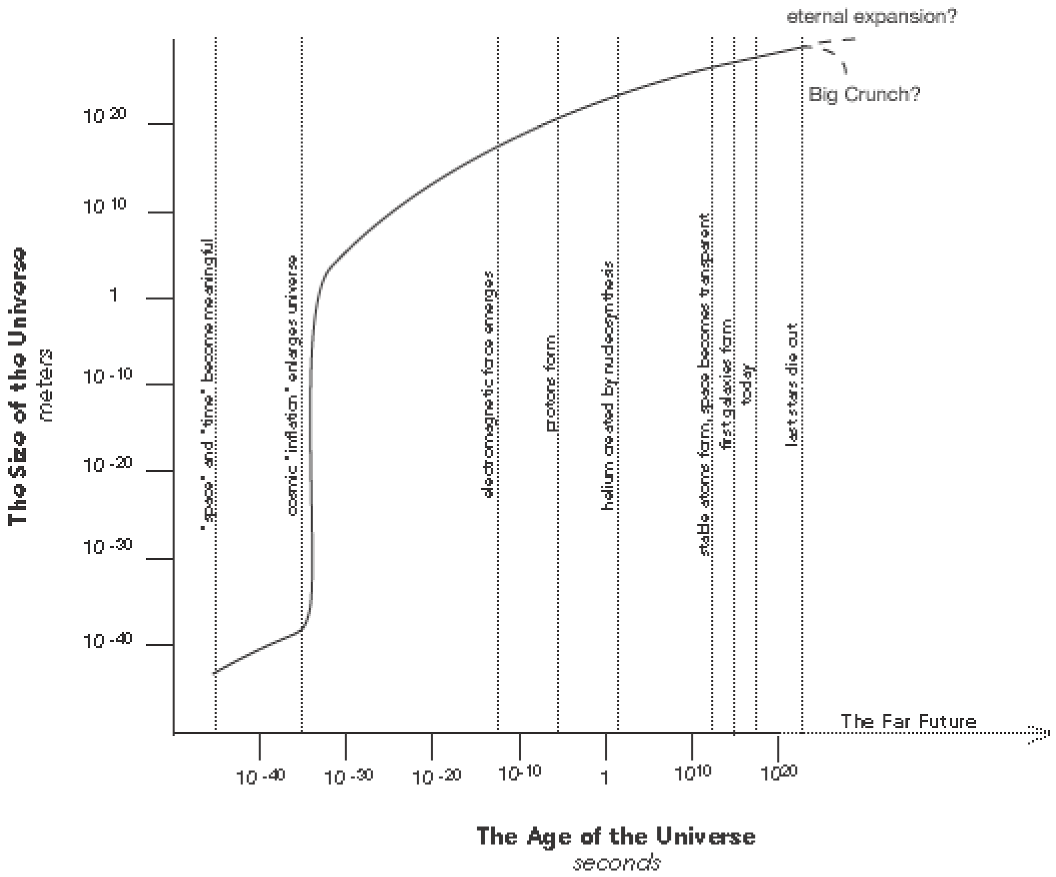
What will happen to the universe depends on how much matter it contains. The reason is that gravity is the main force that governs the universe, and the more matter there is, the stronger that force is. Gravity (which pulls things together) thus competes with expansion (which throws everything apart).

If the total mass of the universe is greater than a certain mass, known as the critical mass, gravity will beat expansion. Eventually the expansion will slow down, stop, and reverse itself. The universe will contract until it reaches an infinitely small and dense state similar to the one at the time of the Big Bang. That point has been dubbed the Big Crunch. In theory, the cycle of expansion and contraction would then repeat. Cosmologists call this fate a closed universe.

On the other hand, if the mass of the universe is less than or equal to the critical mass, expansion will win. The universe will grow forever. After many billions of years, all stars will have died out, no new stars will be able to form, and life as we know it will no longer be able to survive. Eventually even the atoms and their constituent particles will decompose. Cosmologists call this fate an open universe or, if the mass exactly equals the critical mass, a flat universe.

In essence the fate of the universe is no different from throwing a ball up in the air. In that case, too, gravity competes with an initial force: that of your arm. Usually the ball rises, slows down, stops, and then falls back. This corresponds to a closed universe: gravity wins. But if you were strong enough you could send the ball into space and it would never come back to Earth. This corresponds to an open universe: the initial force wins.

Which fate will it be? As you might imagine, measuring the total amount of matter in the universe is not easy. Not only does this require adding up all the stars and galaxies we can see, it also requires adding up all the matter we can’t see: the dark matter whose presence is revealed only by the forces it exerts on visible matter. Right now the observations seem to indicate an open universe, while theory prefers a flat universe. Few think the universe will ever contract in a Big Crunch.



Growing pains. Like a human embryo growing in the womb, the universe started off as a tiny speck and grew to its present size and complexity. As it grew, the various things we take for granted today — space and time, physical forces, subatomic particles, atomic nuclei, atoms, stars, planets, life — were able to form in succession. In the very earliest moments, the rate of growth was much faster than today. This is why we’ve presented this timeline using a logarithmic scale. That is, the step between successive tick marks represents a factor of 10 billion in either size (vertical axis) or time (horizontal axis). The universe may continue to expand forever, or it may eventually stop expanding and contract into a Big Crunch. This diagram is based partly on a sketch by Chris D. Impey, Steward Observatory.