

COSMOLOGY

Misconceptions about the Big Bang **Baffled by the expansion of the universe? You're not alone. Even astronomers frequently get it wrong** By Charles H. Lineweaver and Tamara M. Davis



Image: SLIM FILMS **INFLATING BALLOON** is a good analogy for understanding the expansion of the universe. The galaxies on the surface of the balloon are effectively at rest, and yet as the universe expands, the distance between any two galaxies increases. The galaxies themselves do not increase in size.

The expansion of the universe may be the most important fact we have ever discovered about our origins. You would not be reading this article if the universe had not expanded. Human beings would not exist. Cold molecular things such as life-forms and terrestrial planets could not have come into existence unless the universe, starting from a hot big bang, had expanded and cooled. The formation of all the structures in the universe, from galaxies and stars to planets and *Scientific American* articles, has depended on the expansion.

Forty years ago this July, scientists announced the discovery of definitive evidence for the expansion of the universe from a hotter, denser, primordial state. They had found the cool afterglow of the big bang: the cosmic microwave background radiation. Since this discovery, the expansion and cooling of the universe has been the unifying theme of cosmology, much as Darwinian evolution is the unifying theme of biology. Like Darwinian evolution, cosmic expansion provides the context within which simple structures form and develop over time into complex structures. Without evolution and expansion, modern biology and cosmology make little sense.

The expansion of the universe is like Darwinian evolution in another curious way: most scientists think they understand it, but few agree on what it really means. A century and a half after *On the Origin of Species*, biologists still debate the mechanisms and implications (though not the reality) of Darwinism, while much of the public still flounders in pre-Darwinian cluelessness. Similarly, 75 years after its initial discovery, the expansion of the universe is still widely misunderstood. A prominent cosmologist involved in the interpretation of the cosmic microwave background, James Peebles of Princeton University, wrote in 1993: "The full extent and richness of this picture [the hot big bang model] is not as well understood as I think it ought to be ... even among those making some of the most stimulating contributions to the flow of ideas."

Renowned physicists, authors of astronomy textbooks and prominent popularizers of science have made incorrect, misleading or easily misinterpreted statements about the expansion of the universe. Because expansion is the basis of the big bang model, these misunderstandings are fundamental. Expansion is a beguilingly simple idea, but what exactly does it mean to say the universe is expanding? What does it expand into? Is Earth expanding, too? To add to the befuddlement, the expansion of the universe now seems to be accelerating, a process with truly mind-stretching consequences.

What Is Expansion, Anyway?

When some familiar object expands, such as a sprained ankle or the Roman Empire or a bomb, it gets bigger by expanding into the space around it. Ankles, empires and bombs have centers and edges. Outside the edges, there is room to expand into. The universe does not seem to have an edge or a center or an outside, so how can it expand?

A good analogy is to imagine that you are an ant living on the surface of an inflating balloon. Your world is two-dimensional; the only directions you know are left, right, forward and backward. You have no idea what "up" and "down" mean. One day you realize that your walk to milk your aphids is taking longer than it used to: five minutes one day, six minutes the next day, seven minutes the next. The time it takes to walk to other familiar places is also increasing. You are sure that you are not walking more slowly and that the aphids are milling around randomly in groups, not systematically crawling away from you.

This is the important point: the distances to the aphids are increasing even though the aphids are not walking away. They are just standing there, at rest with respect to the rubber of the balloon, yet the distances to them and between them are increasing. Noticing these facts, you conclude that the ground beneath your feet is expanding. That is very strange because you have walked around your world and found no edge or "outside" for it to expand into.

The expansion of our universe is much like the inflation of a balloon. The distances to remote galaxies are increasing. Astronomers casually say that distant galaxies are "receding" or "moving away" from us, but the galaxies are not traveling through space away from us. They are not fragments of a big bang bomb. Instead the space between the galaxies and us is expanding. Individual galaxies move around at random within clusters, but the clusters of galaxies are essentially at rest. The term "at rest" can be defined rigorously. The microwave background radiation fills the universe and defines a universal reference frame, analogous to the rubber of the balloon, with respect to which motion can be measured.

This balloon analogy should not be stretched too far. From our point of view outside the balloon, the expansion of the curved two-dimensional rubber is possible only because it is embedded in three-dimensional space. Within the third dimension, the balloon has a center, and its surface expands into the surrounding air as it inflates. One might conclude that the expansion of our three-dimensional space requires the presence of a fourth

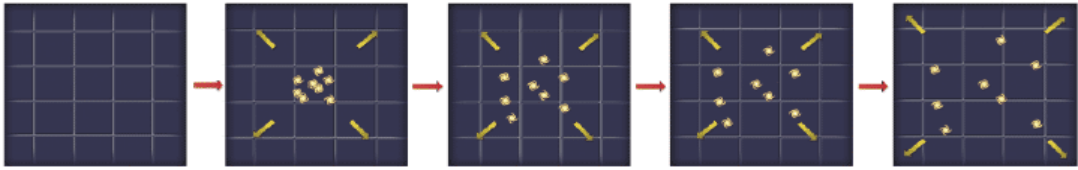
dimension. But in Einstein's general theory of relativity, the foundation of modern cosmology, space is dynamic. It can expand, shrink and curve without being embedded in a higher-dimensional space.

In this sense, the universe is self-contained. It needs neither a center to expand away from nor empty space on the outside (wherever that is) to expand into. When it expands, it does not claim previously unoccupied space from its surroundings. Some newer theories such as string theory do postulate extra dimensions, but as our three-dimensional universe expands, it does not need these extra dimensions to spread into.

WHAT KIND OF EXPLOSION WAS THE BIG BANG?

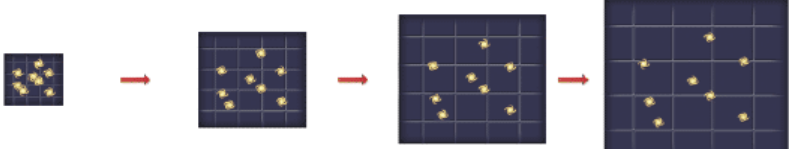
WRONG: The big bang was like a bomb going off at a certain location in previously empty space.

In this view, the universe came into existence when matter exploded out from some particular location. The pressure was highest at the center and lowest in the surrounding void; this pressure difference pushed material outward.



RIGHT: It was an explosion of space itself.

The space we inhabit is itself expanding. There was no center to this explosion; it happened everywhere. The density and pressure were the same everywhere, so there was no pressure difference to drive a conventional explosion.



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Ubiquitous Cosmic Traffic Jam

In our universe, as on the surface of the balloon, everything recedes from everything else. Thus, the big bang was not an explosion *in* space; it was more like an explosion *of* space. It did not go off at a particular location and spread out from there into some imagined preexisting void. It occurred everywhere at once.

If one imagines running the clock backward in time, any given region of the universe shrinks and all galaxies in it get closer and closer until they smash together in a cosmic traffic jam--the big bang. This traffic-jam analogy might imply local congestion that you could avoid if you listened to the traffic report on the radio. But the big bang was an unavoidable traffic jam. It was like having the surface of Earth and all its highways shrink while cars remained the same size. Eventually the cars will be bumper to bumper on every road. No radio broadcast is going to help you around that kind of traffic jam. The congestion is everywhere.

Similarly, the big bang happened everywhere--in the room in which you are reading this article, in a spot just to the left of Alpha Centauri, everywhere. It was not a bomb going off at a particular spot that we can identify as the center of the explosion. Likewise, in the

balloon analogy, there is no special place on the surface of the balloon that is the center of the expansion.

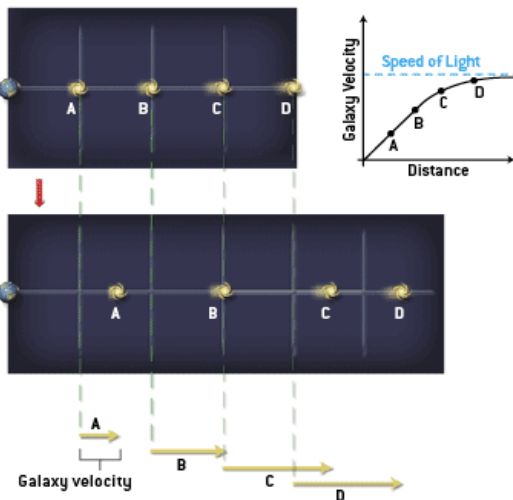
This ubiquity of the big bang holds no matter how big the universe is or even whether it is finite or infinite in size. Cosmologists sometimes state that the universe used to be the size of a grapefruit, but what they mean is that the part of the universe we can now see--our observable universe--used to be the size of a grapefruit.

Observers living in the Andromeda galaxy and beyond have their own observable universes that are different from but overlap with ours. Andromedans can see galaxies we cannot, simply by virtue of being slightly closer to them, and vice versa. Their observable universe also used to be the size of a grapefruit. Thus, we can conceive of the early universe as a pile of overlapping grapefruits that stretches infinitely in all directions. Correspondingly, the idea that the big bang was "small" is misleading. The totality of space could be infinite. Shrink an infinite space by an arbitrary amount, and it is still infinite.

CAN GALAXIES RECEDE FASTER THAN LIGHT?

WRONG: Of course not. Einstein's special theory of relativity forbids that.

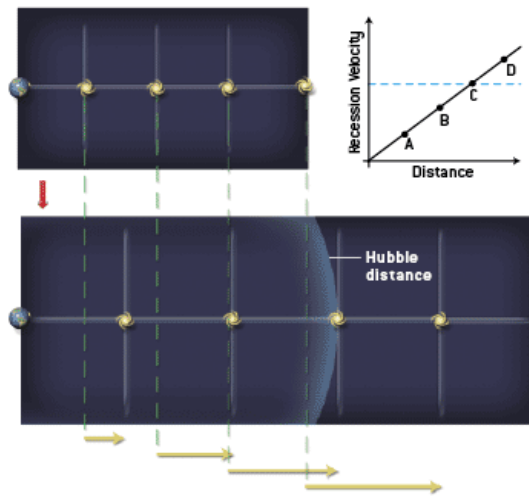
Consider a patch of space containing some galaxies. The galaxies move away from us—the farther the galaxy, the faster its velocity (yellow arrows). If light speed is the ultimate limit, the galaxy velocity must eventually plateau (graph).



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RIGHT: Sure they can. Special relativity does not apply to recession velocity.

In expanding space, recession velocity keeps increasing with distance. Beyond a certain distance, known as the Hubble distance, it exceeds the speed of light. This is not a violation of relativity, because recession velocity is caused not by motion *through* space but by the expansion of space.



Receding Faster Than Light

Another set of misconceptions involves the quantitative description of expansion. The rate at which the distance between galaxies increases follows a distinctive pattern discovered by American astronomer Edwin Hubble in 1929: the recession velocity of a galaxy away from us (v) is directly proportional to its distance from us (d), or $v = Hd$. The proportionality constant, H , is known as the Hubble constant and quantifies how fast space is stretching--not just around us but around any observer in the universe.

Some people get confused by the fact that some galaxies do not obey Hubble's law. Andromeda, our nearest large galactic neighbor, is actually moving toward us, not away. Such exceptions arise because Hubble's law describes only the average behavior of galaxies. Galaxies can also have modest local motions as they mill around and gravitationally pull on one another--as the Milky Way and Andromeda are doing. Distant galaxies also have small local velocities, but from our perspective (at large values of d) these random velocities are swamped by large recession velocities (v). Thus, for those galaxies, Hubble's law holds with good precision.

Notice that, according to Hubble's law, the universe does not expand at a single speed. Some galaxies recede from us at 1,000 kilometers per second, others (those twice as distant) at 2,000 km/s, and so on. In fact, Hubble's law predicts that galaxies beyond a certain distance, known as the Hubble distance, recede faster than the speed of light. For the measured value of the Hubble constant, this distance is about 14 billion light-years.

Does this prediction of faster-than-light galaxies mean that Hubble's law is wrong? Doesn't Einstein's special theory of relativity say that nothing can have a velocity exceeding that of light? This question has confused generations of students. The solution is that special relativity applies only to "normal" velocities--motion through space. The velocity in Hubble's law is a recession velocity caused by the expansion of space, not a motion through space. It is a general relativistic effect and is not bound by the special relativistic limit. Having a recession velocity greater than the speed of light does not violate special relativity. It is still true that nothing ever overtakes a light beam.

Stretching and Cooling

The primary observation that the universe is expanding emerged between 1910 and 1930. Atoms emit and absorb light of specific wavelengths, as measured in laboratory experiments. The same patterns show up in the light from distant galaxies, except that the patterns have been shifted to longer wavelengths. Astronomers say that the galactic light has been redshifted. The explanation is straightforward: As space expands, light waves get stretched. If the universe doubles in size during the waves' journey, their wavelengths double and their energy is halved.

This process can be described in terms of temperature. The photons emitted by a body collectively have a temperature--a certain distribution of energy that reflects how hot the body is. As the photons travel through expanding space, they lose energy and their

temperature decreases. In this way, the universe cools as it expands, much as compressed air in a scuba tank cools when it is released and allowed to expand. For example, the microwave background radiation currently has a temperature of about three kelvins, whereas the process that released the radiation occurred at a temperature of about 3,000 kelvins. Since the time of the emission of this radiation, the universe has increased in size by a factor of 1,000, so the temperature of the photons has decreased by the same factor. By observing the gas in distant galaxies, astronomers have directly measured the temperature of the radiation in the distant past. These measurements confirm that the universe has been cooling with time.

Misunderstandings about the relation between redshift and velocity abound. The redshift caused by the expansion is often confused with the more familiar redshift generated by the Doppler effect. The normal Doppler effect causes sound waves to get longer if the source of the sound is moving away--for example, a receding ambulance siren. The same principle also applies to light waves, which get longer if the source of the light is moving through space away from us.

This is similar, but not identical, to what happens to the light from distant galaxies. The cosmological redshift is not a normal Doppler shift. Astronomers frequently refer to it as such, and in doing so they have done their students a serious disservice. The Doppler redshift and the cosmological redshift are governed by two distinct formulas. The first comes from special relativity, which does not take into account the expansion of space, and the second comes from general relativity, which does. The two formulas are nearly the same for nearby galaxies but diverge for distant galaxies.

According to the usual Doppler formula, objects whose velocity through space approaches light speed have redshifts that approach infinity. Their wavelengths become too long to observe. If that were true for galaxies, the most distant visible objects in the sky would be receding at velocities just shy of the speed of light. But the cosmological redshift formula leads to a different conclusion. In the current standard model of cosmology, galaxies with a redshift of about 1.5--that is, whose light has a wavelength 150 percent longer than the laboratory reference value--are receding at the speed of light. Astronomers have observed about 1,000 galaxies with redshifts larger than 1.5. That is, they have observed about 1,000 objects receding from us faster than the speed of light. Equivalently, we are receding from those galaxies faster than the speed of light. The radiation of the cosmic microwave background has traveled even farther and has a redshift of about 1,000. When the hot plasma of the early universe emitted the radiation we now see, it was receding from our location at about 50 times the speed of light.

Running to Stay Still

The idea of seeing faster-than-light galaxies may sound mystical, but it is made possible by changes in the expansion rate. Imagine a light beam that is farther than the Hubble distance of 14 billion light-years and trying to travel in our direction. It is moving toward us at the speed of light with respect to its local space, but its local space is receding from us faster than the speed of light. Although the light beam is traveling toward us at the

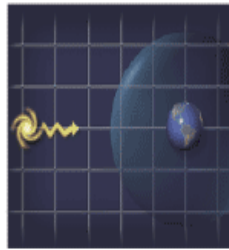
maximum speed possible, it cannot keep up with the stretching of space. It is a bit like a child trying to run the wrong way on a moving sidewalk. Photons at the Hubble distance are like the Red Queen and Alice, running as fast as they can just to stay in the same place.

One might conclude that the light beyond the Hubble distance would never reach us and that its source would be forever undetectable. But the Hubble distance is not fixed, because the Hubble constant, on which it depends, changes with time. In particular, the constant is proportional to the rate of increase in the distance between two galaxies, divided by that distance. (Any two galaxies can be used for this calculation.) In models of the universe that fit the observational data, the denominator increases faster than the numerator, so the Hubble constant decreases. In this way, the Hubble distance gets larger. As it does, light that was initially just outside the Hubble distance and receding from us can come within the Hubble distance. The photons then find themselves in a region of space that is receding slower than the speed of light. Thereafter they can approach us.

CAN WE SEE GALAXIES RECEDING FASTER THAN LIGHT?

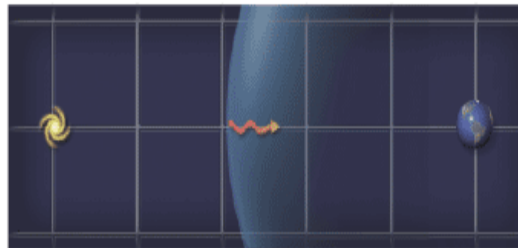
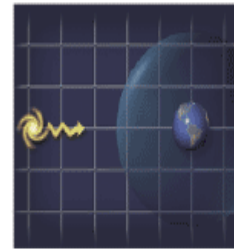
WRONG: Of course not. Light from those galaxies never reaches us.

A galaxy farther than the Hubble distance (*sphere*) recedes from us faster than light. It emits a photon (*yellow squiggle*). As space expands, the photon is dragged away like someone trying to swim against the current. The photon never reaches us.



RIGHT: Sure we can, because the expansion rate changes over time.

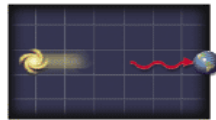
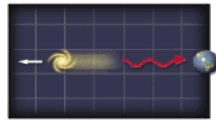
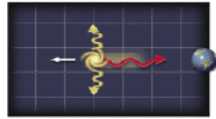
The photon initially is unable to approach us. But the Hubble distance is not constant; it is increasing and can grow to encompass the photon. Once that happens, the photon approaches us and eventually reaches us.



WHY IS THERE A COSMIC REDSHIFT?

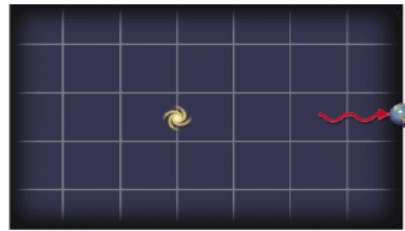
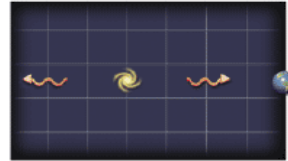
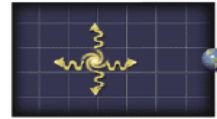
WRONG: Because receding galaxies are moving through space and exhibit a Doppler shift.

In the Doppler effect, a galaxy's movement away from the observer stretches the light waves, making them redder (*top*). The wavelength of light then stays the same during its journey through space (*middle*). The observer detects the light, measures its Doppler redshift and computes the galaxy velocity (*bottom*).



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RIGHT: Because expanding space stretches all light waves as they propagate.



Galaxies hardly move through space, so they emit light with nearly the same wavelength in all directions (*top*). The wavelength gets longer during the journey, because space is expanding. Thus, the light gradually reddens (*middle and bottom*). The amount of redshift differs from what a Doppler shift would produce.

The galaxy they came from, though, may continue to recede superluminally. Thus, we can observe light from galaxies that have always been and will always be receding faster than the speed of light. Another way to put it is that the Hubble distance is not fixed and does not mark the edge of the observable universe.

What does mark the edge of observable space? Here again there has been confusion. If space were not expanding, the most distant object we could see would now be about 14 billion light-years away from us, the distance light could have traveled in the 14 billion years since the big bang. But because the universe is expanding, the space traversed by a photon expands behind it during the voyage. Consequently, the current distance to the most distant object we can see is about three times farther, or 46 billion light-years.

The recent discovery that the rate of cosmic expansion is accelerating makes things even more interesting. Previously, cosmologists thought that we lived in a decelerating universe and that ever more galaxies would come into view. In an accelerating universe, however, we are surrounded by a boundary beyond which occur events we will never see--a cosmic event horizon. If light from galaxies receding faster than light is to reach us, the Hubble distance has to increase, but in an accelerating universe, it stops increasing. Distant events may send out light beams aimed in our direction, but this light is trapped beyond the Hubble distance by the acceleration of the expansion.

An accelerating universe, then, resembles a black hole in that it has an event horizon, an

edge beyond which we cannot see. The current distance to our cosmic event horizon is 16 billion light-years, well within our observable range. Light emitted from galaxies that are now beyond the event horizon will never be able to reach us; the distance that currently corresponds to 16 billion light-years will expand too quickly. We will still be able to see events that took place in those galaxies before they crossed the horizon, but subsequent events will be forever beyond our view.

Is Brooklyn Expanding?

In *Annie Hall*, the movie character played by the young Woody Allen explains to his doctor and mother why he can't do his homework. "The universe is expanding.... The universe is everything, and if it's expanding, someday it will break apart and that would be the end of everything!" But his mother knows better: "You're here in Brooklyn. Brooklyn is not expanding!"

His mother is right. Brooklyn is not expanding. People often assume that as space expands, everything in it expands as well. But this is not true. Expansion by itself--that is, a coasting expansion neither accelerating nor decelerating--produces no force. Photon wavelengths expand with the universe because, unlike atoms and cities, photons are not coherent objects whose size has been set by a compromise among forces. A changing rate of expansion does add a new force to the mix, but even this new force does not make objects expand or contract.

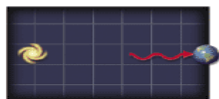
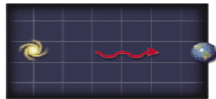
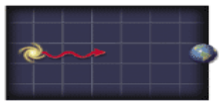
For example, if gravity got stronger, your spinal cord would compress until the electrons in your vertebrae reached a new equilibrium slightly closer together. You would be a shorter person, but you would not continue to shrink. In the same way, if we lived in a universe dominated by the attractive force of gravity, as most cosmologists thought until a few years ago, the expansion would decelerate, putting a gentle squeeze on bodies in the universe, making them reach a smaller equilibrium size. Having done so, they would not keep shrinking.

In fact, in our universe the expansion is accelerating, and that exerts a gentle outward force on bodies. Consequently, bound objects are slightly larger than they would be in a nonaccelerating universe, because the equilibrium among forces is reached at a slightly larger size. At Earth's surface, the outward acceleration away from the planet's center equals a tiny fraction (10^{-30}) of the normal inward gravitational acceleration. If this acceleration is constant, it does not make Earth expand; rather the planet simply settles into a static equilibrium size slightly larger than the size it would have attained.

HOW LARGE IS THE OBSERVABLE UNIVERSE?

WRONG: The universe is 14 billion years old, so the radius of the observable part is 14 billion light-years.

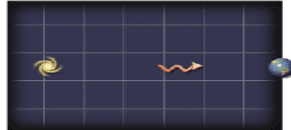
Consider the most distant observable galaxy—one whose photons, emitted shortly after the big bang, are only now reaching us. A light-year is the distance photons travel in one year. So a photon from that galaxy has traveled 14 billion light-years.



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RIGHT: Because space is expanding, the observable part of our universe has a radius of more than 14 billion light-years.

As a photon travels, the space it traverses expands. By the time it reaches us, the total distance to the originating galaxy is larger than a simple calculation based on the travel time might imply—about three times as large.

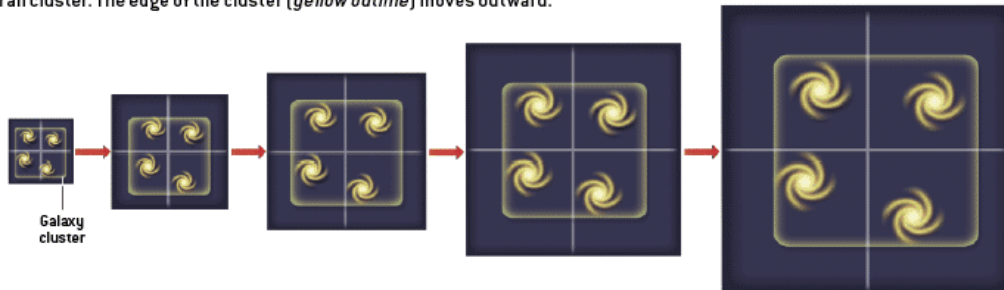


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DO OBJECTS INSIDE THE UNIVERSE EXPAND, TOO?

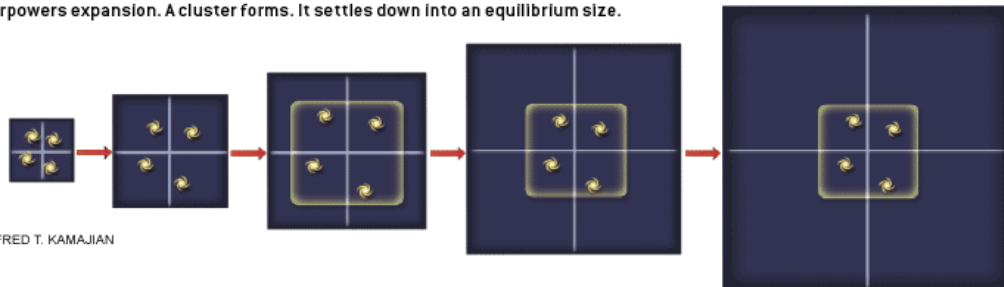
WRONG: Yes. Expansion causes the universe and everything in it to grow.

Consider galaxies in a cluster. As the universe gets bigger, so do the galaxies and the overall cluster. The edge of the cluster (yellow outline) moves outward.



RIGHT: No. The universe grows, but coherent objects inside it do not.

Neighboring galaxies initially get pulled apart, but eventually their mutual gravity overpowers expansion. A cluster forms. It settles down into an equilibrium size.



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This reasoning changes if acceleration is not constant, as some cosmologists have speculated. If the acceleration itself increased, it could eventually grow strong enough to tear apart all structures, leading to a "big rip." But this rip would occur not because of expansion or acceleration per se but because of an accelerating acceleration.

The big bang model is based on observations of expansion, the cosmic microwave background, the chemical composition of the universe and the clumping of matter. Like all scientific ideas, the model may one day be superseded. But it fits the current data better than any other model we have. As new precise measurements enable cosmologists to understand expansion and acceleration better, they can ask even more fundamental questions about the earliest times and largest scales of the universe. What caused the expansion? Many cosmologists attribute it to a process known as inflation, a type of accelerating expansion. But that can only be a partial answer, because it seems that to start inflating, the universe already had to be expanding. And what about the largest scales, beyond what we can see? Do different parts of the universe expand by different amounts, such that our universe is a single inflationary bubble of a much larger multiverse? Nobody knows. Although many questions remain, increasingly precise observations suggest that the universe will expand forever. We hope, though, the confusion about the expansion will shrink.

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