

Analysis of Planck data also shows that ordinary matter (mainly protons and neutrons) makes up 4.9% of the total density. Dark matter plus normal matter add up to 31.5% of the total density. Dark energy contributes the remaining 68.5%. The age of the universe at decoupling—that is, when the CMB was emitted—was 380,000 years.

Perhaps the most surprising result from the high-precision measurements by WMAP and the even higher-precision measurements from Planck is that there were no surprises. The model of cosmology with ordinary matter at about 5%, dark matter at about 25%, and dark energy about 70% has survived since the late 1990s when cosmologists were forced in that direction by the supernovae data. In other words, the very strange universe that we have been describing, with only about 5% of its contents being made up of the kinds of matter we are familiar with here on Earth, really seems to be the universe we live in.

After the CMB was emitted, the universe continued to expand and cool off. By 400 to 500 million years after the Big Bang, the very first stars and galaxies had already formed. Deep in the interiors of stars, matter was reheated, nuclear reactions were ignited, and the more gradual synthesis of the heavier elements that we have discussed throughout this book began.

We conclude this quick tour of our model of the early universe with a reminder. You must not think of the Big Bang as a *localized* explosion *in space*, like an exploding superstar. There were no boundaries and there was no single site where the explosion happened. It was an explosion *of space* (and time and matter and energy) that happened everywhere in the universe. All matter and energy that exist today, including the particles of which you are made, came from the Big Bang. We were, and still are, in the midst of a Big Bang; it is all around us.

29.5 WHAT IS THE UNIVERSE REALLY MADE OF?

Learning Objectives

By the end of this section, you will be able to:

- › Specify what fraction of the density of the universe is contributed by stars and galaxies and how much ordinary matter (such as hydrogen, helium, and other elements we are familiar with here on Earth) makes up the overall density
- › Describe how ideas about the contents of the universe have changed over the last 50 years
- › Explain why it is so difficult to determine what dark matter really is
- › Explain why dark matter helped galaxies form quickly in the early universe
- › Summarize the evolution of the universe from the time the CMB was emitted to the present day

The model of the universe we described in the previous section is the simplest model that explains the observations. It assumes that general relativity is the correct theory of gravity throughout the universe. With this assumption, the model then accounts for the existence and structure of the CMB; the abundances of the light elements deuterium, helium, and lithium; and the acceleration of the expansion of the universe. All of the observations to date support the validity of the model, which is referred to as the standard (or concordance) model of cosmology.

Figure 29.21 and **Table 29.2** summarize the current best estimates of the contents of the universe. Luminous matter in stars and galaxies and neutrinos contributes about 1% of the mass required to reach critical density. Another 4% is mainly in the form of hydrogen and helium in the space between stars and in intergalactic space. Dark matter accounts for about an additional 27% of the critical density. The mass equivalent of dark energy (according to $E = mc^2$) then supplies the remaining 68% of the critical density.

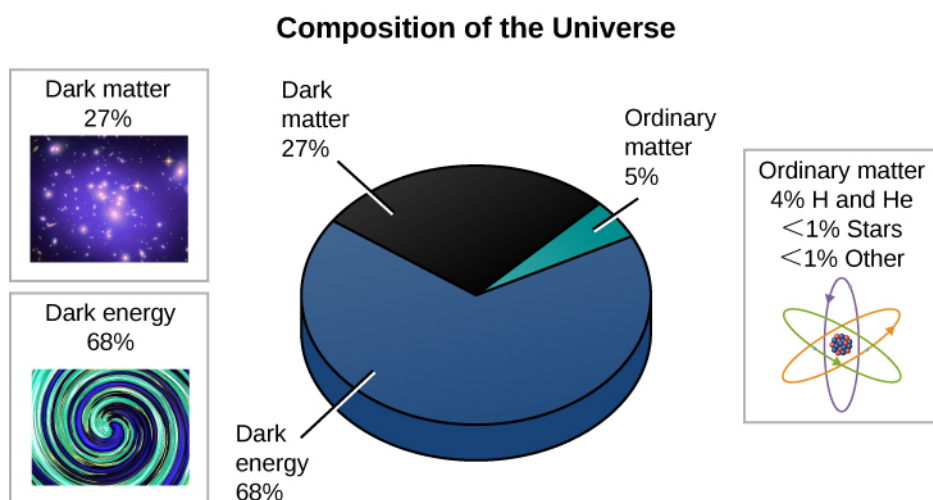


Figure 29.21 Composition of the Universe. Only about 5% of all the mass and energy in the universe is matter with which we are familiar here on Earth. Most ordinary matter consists of hydrogen and helium located in interstellar and intergalactic space. Only about one-half of 1% of the critical density of the universe is found in stars. Dark matter and dark energy, which have not yet been detected in earthbound laboratories, account for 95% of the contents of the universe.

What Different Kinds of Objects Contribute to the Density of the Universe

Object	Density as a Percent of Critical Density
Luminous matter (stars, etc.)	<1
Hydrogen and helium in interstellar and intergalactic space	4
Dark matter	27
Equivalent mass density of the dark energy	68

Table 29.2

This table should shock you. What we are saying is that 95% of the stuff of the universe is either dark matter or dark energy—neither of which has ever been detected in a laboratory here on Earth. This whole textbook, which has focused on objects that emit electromagnetic radiation, has generally been ignoring 95% of what is out there. Who says there aren't big mysteries yet to solve in science!

Figure 29.22 shows how our ideas of the composition of the universe have changed over just the past three decades. The fraction of the universe that we think is made of the same particles as astronomy students has been decreasing steadily.

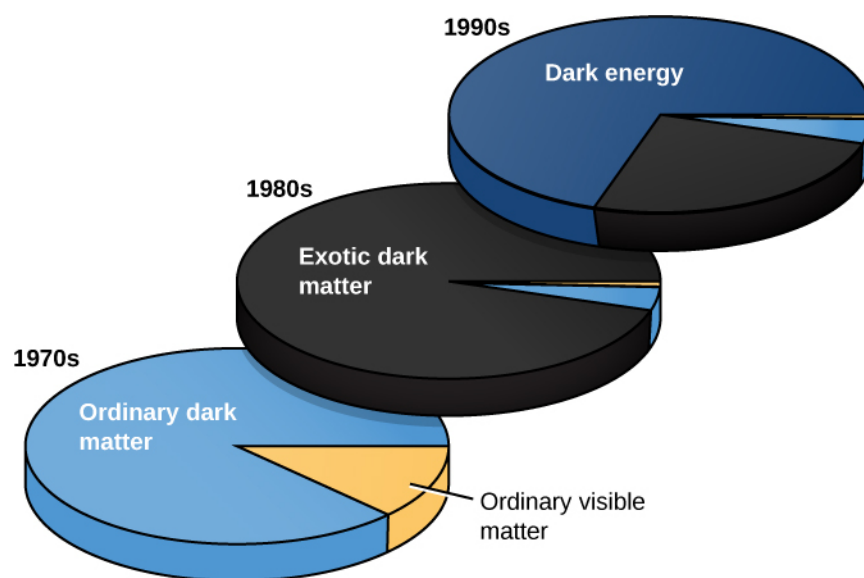


Figure 29.22 Changing Estimates of the Content of the Universe. This diagram shows the changes in our understanding of the contents of the universe over the past three decades. In the 1970s, we suspected that most of the matter in the universe was invisible, but we thought that this matter might be ordinary matter (protons, neutrons, etc.) that was simply not producing electromagnetic radiation. By the 1980s, it was becoming likely that most of the dark matter was made of something we had not yet detected on Earth. By the late 1990s, a variety of experiments had shown that we live in a critical -density universe and that dark energy contributes about 70% of what is required to reach critical density. Note how the estimate of the relative importance of ordinary luminous matter (shown in yellow) has diminished over time.

What Is Dark Matter?

Many astronomers find the situation we have described very satisfying. Several independent experiments now agree on the type of universe we live in and on the inventory of what it contains. We seem to be very close to having a cosmological model that explains nearly everything. Others are not yet ready to jump on the bandwagon. They say, “show me the 96% of the universe we can’t detect directly—for example, find me some dark matter!”

At first, astronomers thought that **dark matter** might be hidden in objects that appear dark because they emit no light (e.g., black holes) or that are too faint to be observed at large distances (e.g., planets or white dwarfs). However, these objects would be made of ordinary matter, and the deuterium abundance tells us that no more than 5% of the critical density consists of ordinary matter.

Another possible form that dark matter can take is some type of elementary particle that we have not yet detected here on Earth—a particle that has mass and exists in sufficient abundance to contribute 23% of the critical density. Some physics theories predict the existence of such particles. One class of these particles has been given the name WIMPs, which stands for **weakly interacting massive particles**. Since these particles do not participate in nuclear reactions leading to the production of deuterium, the deuterium abundance puts no limits on how many WIMPs might be in the universe. (A number of other exotic particles have also been suggested as prime constituents of dark matter, but we will confine our discussion to WIMPs as a useful example.)

If large numbers of WIMPs do exist, then some of them should be passing through our physics laboratories right now. The trick is to catch them. Since by definition they interact only weakly (infrequently) with other matter, the chances that they will have a measurable effect are small. We don’t know the mass of these particles, but various theories suggest that it might be a few to a few hundred times the mass of a proton. If WIMPs are 60 times the mass of a proton, there would be about 10 million of them passing through your outstretched hand every second—with absolutely no effect on you. If that seems too mind-boggling, bear in mind that neutrinos interact weakly with ordinary matter, and yet we were able to “catch” them eventually.

Despite the challenges, more than 30 experiments designed to detect WIMPs are in operation or in the planning stages. Predictions of how many times WIMPs might actually collide with the nucleus of an atom in the instrument designed to detect them are in the range of 1 event per year to 1 event per 1000 years per kilogram of detector. The detector must therefore be large. It must be shielded from radioactivity or other types of particles, such as neutrons, passing through it, and hence these detectors are placed in deep mines. The energy imparted to an atomic nucleus in the detector by collision with a WIMP will be small, and so the detector must be cooled to a very low temperature.

The WIMP detectors are made out of crystals of germanium, silicon, or xenon. The detectors are cooled to a few thousandths of a degree—very close to absolute zero. That means that the atoms in the detector are so cold that they are scarcely vibrating at all. If a dark matter particle collides with one of the atoms, it will cause the whole crystal to vibrate and the temperature therefore to increase ever so slightly. Some other interactions may generate a detectable flash of light.

A different kind of search for WIMPs is being conducted at the Large Hadron Collider (LHC) at CERN, Europe's particle physics lab near Geneva, Switzerland. In this experiment, protons collide with enough energy potentially to produce WIMPs. The LHC detectors cannot detect the WIMPs directly, but if WIMPs are produced, they will pass through the detectors, carrying energy away with them. Experimenters will then add up all the energy that they detect as a result of the collisions of protons to determine if any energy is missing.

So far, none of these experiments has detected WIMPs. Will the newer experiments pay off? Or will scientists have to search for some other explanation for dark matter? Only time will tell ([Figure 29.23](#)).



Figure 29.23 Dark Matter. This cartoon from NASA takes a humorous look at how little we yet understand about dark matter. (credit: NASA)

Dark Matter and the Formation of Galaxies

As elusive as dark matter may be in the current-day universe, galaxies could not have formed quickly without it. Galaxies grew from density fluctuations in the early universe, and some had already formed only about

400–500 million years after the Big Bang. The observations with WMAP, Planck, and other experiments give us information on the size of those density fluctuations. It turns out that the density variations we observe are too small to have formed galaxies so soon after the Big Bang. In the hot, early universe, energetic photons collided with hydrogen and helium, and kept them moving so rapidly that gravity was still not strong enough to cause the atoms to come together to form galaxies. How can we reconcile this with the fact that galaxies *did* form and are all around us?

Our instruments that measure the CMB give us information about density fluctuations only for *ordinary matter*, which interacts with radiation. Dark matter, as its name indicates, does not interact with photons at all. Dark matter could have had much greater variations in density and been able to come together to form gravitational “traps” that could then have begun to attract ordinary matter immediately after the universe became transparent. As ordinary matter became increasingly concentrated, it could have turned into galaxies quickly thanks to these dark matter traps.

For an analogy, imagine a boulevard with traffic lights every half mile or so. Suppose you are part of a motorcade of cars accompanied by police who lead you past each light, even if it is red. So, too, when the early universe was opaque, radiation interacted with ordinary matter, imparting energy to it and carrying it along, sweeping past the concentrations of dark matter. Now suppose the police leave the motorcade, which then encounters some red lights. The lights act as traffic traps; approaching cars now have to stop, and so they bunch up. Likewise, after the early universe became transparent, ordinary matter interacted with radiation only occasionally and so could fall into the dark matter traps.

The Universe in a Nutshell

In the previous sections of this chapter, we traced the evolution of the universe progressively further back in time. Astronomical discovery has followed this path historically, as new instruments and new techniques have allowed us to probe ever closer to the beginning of time. The rate of expansion of the universe was determined from measurements of nearby galaxies. Determinations of the abundances of deuterium, helium, and lithium based on nearby stars and galaxies were used to put limits on how much ordinary matter is in the universe. The motions of stars in galaxies and of galaxies within clusters of galaxies could only be explained if there were large quantities of dark matter. Measurements of supernovae that exploded when the universe was about half as old as it is now indicated that the rate of expansion of the universe has sped up since those explosions occurred. Observations of extremely faint galaxies show that galaxies had begun to form when the universe was only 400–500 million years old. And observations of the CMB confirmed early theories that the universe was initially very hot.

But all this moving further and further backward in time might have left you a bit dizzy. So now let’s instead show how the universe evolves as time moves forward.

Figure 29.24 summarizes the entire history of the observable universe from the beginning in a single diagram. The universe was very hot when it began to expand. We have fossil remnants of the very early universe in the form of neutrons, protons, electrons, and neutrinos, and the atomic nuclei that formed when the universe was 3–4 minutes old: deuterium, helium, and a small amount of lithium. Dark matter also remains, but we do not yet know what form it is in.

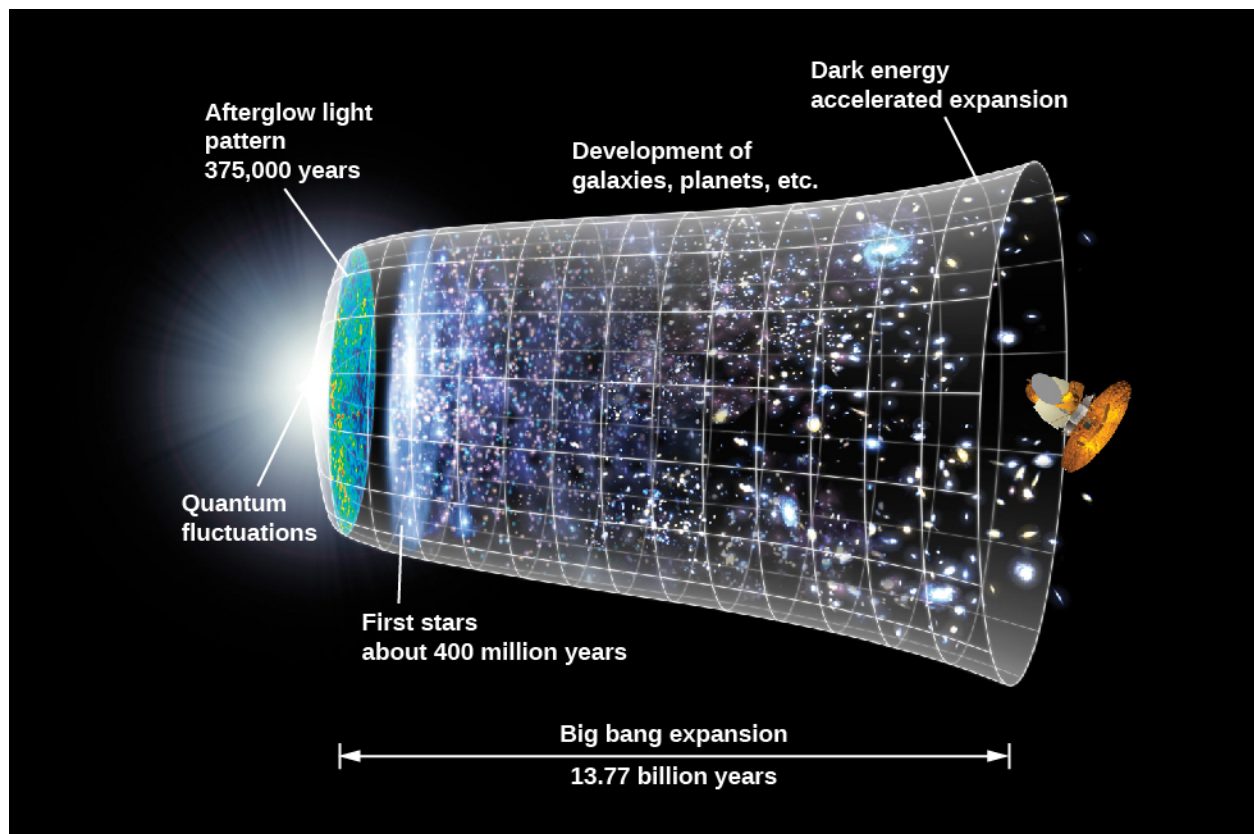


Figure 29.24 History of the Universe. This image summarizes the changes that have occurred in the universe during the last 13.8 billion years. Protons, deuterium, helium, and some lithium were produced in the initial fireball. About 380,000 years after the Big Bang, the universe became transparent to electromagnetic radiation for the first time. COBE, WMAP, Planck, and other instruments have been used to study the radiation that was emitted at that time and that is still visible today (the CMB). The universe was then dark (except for this background radiation) until the first stars and galaxies began to form only a few hundred million years after the Big Bang. Existing space and ground-based telescopes have made substantial progress in studying the subsequent evolution of galaxies. (credit: modification of work by NASA/WMAP Science Team)

The universe gradually cooled; when it was about 380,000 years old, and at a temperature of about 3000 K, electrons combined with protons to form hydrogen atoms. At this point, as we saw, the universe became transparent to light, and astronomers have detected the CMB emitted at this time. The universe still contained no stars or galaxies, and so it entered what astronomers call “the dark ages” (since stars were not lighting up the darkness). During the next several hundred million years, small fluctuations in the density of the dark matter grew, forming gravitational traps that concentrated the ordinary matter, which began to form galaxies about 400–500 million years after the Big Bang.

By the time the universe was about a billion years old, it had entered its own renaissance: it was again blazing with radiation, but this time from newly formed stars, star clusters, and small galaxies. Over the next several billion years, small galaxies merged to form the giants we see today. Clusters and superclusters of galaxies began to grow, and the universe eventually began to resemble what we see nearby.

During the next 20 years, astronomers plan to build giant new telescopes both in space and on the ground to explore even further back in time. In 2018, the James Webb Space Telescope, a 6.5-meter telescope that is the successor to the Hubble Space Telescope, will be launched and assembled in space. The predictions are that with this powerful instrument (see [Figure 29.1](#)) we should be able to look back far enough to analyze in detail the formation of the first galaxies.

29.6 THE INFLATIONARY UNIVERSE

Learning Objectives

By the end of this section, you will be able to:

- Describe two important properties of the universe that the simple Big Bang model cannot explain
- Explain why these two characteristics of the universe can be accounted for if there was a period of rapid expansion (inflation) of the universe just after the Big Bang
- Name the four forces that control all physical processes in the universe

The hot Big Bang model that we have been describing is remarkably successful. It accounts for the expansion of the universe, explains the observations of the CMB, and correctly predicts the abundances of the light elements. As it turns out, this model also predicts that there should be exactly three types of neutrinos in nature, and this prediction has been confirmed by experiments with high-energy accelerators. We can't relax just yet, however. This standard model of the universe doesn't explain *all* the observations we have made about the universe as a whole.

Problems with the Standard Big Bang Model

There are a number of characteristics of the universe that can only be explained by considering further what might have happened before the emission of the CMB. One problem with the standard Big Bang model is that it does not explain why the density of the universe is equal to the critical density. The mass density could have been, after all, so low and the effects of dark energy so high that the expansion would have been too rapid to form any galaxies at all. Alternatively, there could have been so much matter that the universe would have already begun to contract long before now. Why is the universe balanced so precisely on the knife edge of the critical density?

Another puzzle is the remarkable *uniformity* of the universe. The temperature of the CMB is the same to about 1 part in 100,000 everywhere we look. This sameness might be expected if all the parts of the visible universe were in contact at some point in time and had the time to come to the same temperature. In the same way, if we put some ice into a glass of lukewarm water and wait a while, the ice will melt and the water will cool down until they are the same temperature.

However, if we accept the standard Big Bang model, all parts of the visible universe were *not* in contact at any time. The fastest that information can go from one point to another is the speed of light. There is a maximum distance that light can have traveled from any point since the time the universe began—that's the distance light could have covered since then. This distance is called that point's *horizon distance* because anything farther away is "below its horizon"—unable to make contact with it. One region of space separated by more than the horizon distance from another has been completely isolated from it through the entire history of the universe.

If we measure the CMB in two opposite directions in the sky, we are observing regions that were significantly beyond each other's horizon distance at the time the CMB was emitted. We can see both regions, but *they* can never have seen each other. Why, then, are their temperatures so precisely the same? According to the standard Big Bang model, they have never been able to exchange information, and there is no reason they should have identical temperatures. (It's a little like seeing the clothes that all the students wear at two schools in different parts of the world become identical, without the students ever having been in contact.) The only explanation we could suggest was simply that the universe somehow *started out* being absolutely uniform (which is like saying all students were born liking the same clothes). Scientists are always uncomfortable when they must appeal to a special set of initial conditions to account for what they see.

The Inflationary Hypothesis

Some physicists suggested that these fundamental characteristics of the cosmos—its flatness and uniformity—can be explained if shortly after the Big Bang (and before the emission of the CMB), the universe experienced a sudden increase in size. A model universe in which this rapid, early expansion occurs is called an **inflationary universe**. The inflationary universe is identical to the Big Bang universe for all time after the first 10^{-30} second. Prior to that, the model suggests that there was a brief period of extraordinarily rapid expansion or inflation, during which the scale of the universe increased by a factor of about 10^{50} times more than predicted by standard Big Bang models (Figure 29.25).

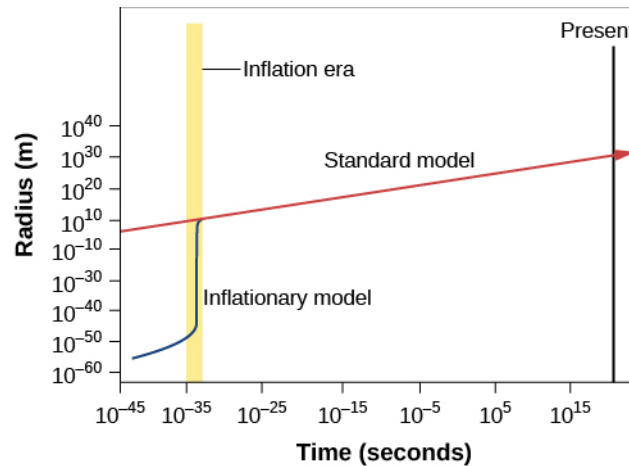


Figure 29.25 Expansion of the Universe. This graph shows how the scale factor of the observable universe changes with time for the standard Big Bang model (red line) and for the inflationary model (blue line). (Note that the time scale at the bottom is extremely compressed.) During inflation, regions that were very small and in contact with each other are suddenly blown up to be much larger and outside each other's horizon distance. The two models are the same for all times after 10^{-30} second.

Prior to (and during) inflation, all the parts of the universe that we can now see were so small and close to each other that they *could* exchange information, that is, the horizon distance included all of the universe that we can now observe. Before (and during) inflation, there was adequate time for the observable universe to homogenize itself and come to the same temperature. Then, inflation expanded those regions tremendously, so that many parts of the universe are now beyond each other's horizon.

Another appeal of the inflationary model is its prediction that the density of the universe should be exactly equal to the critical density. To see why this is so, remember that curvature of spacetime is intimately linked to the density of matter. If the universe began with some curvature of its spacetime, one analogy for it might be the skin of a balloon. The period of inflation was equivalent to blowing up the balloon to a tremendous size. The universe became so big that from our vantage point, no curvature should be visible (Figure 29.26). In the same way, Earth's surface is so big that it looks flat to us no matter where we are. Calculations show that a universe with no curvature is one that is at critical density. Universes with densities either higher or lower than the critical density would show marked curvature. But we saw that the observations of the CMB in Figure 29.18, which show that the universe has critical density, rule out the possibility that space is significantly curved.

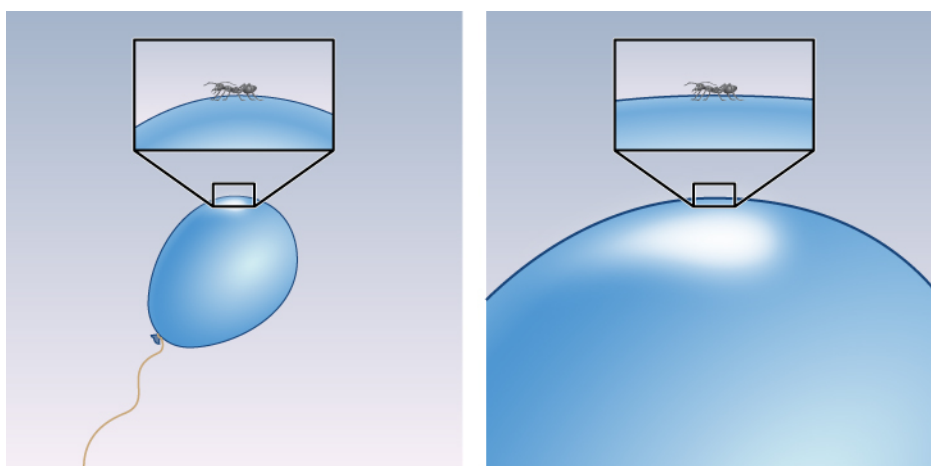


Figure 29.26 Analogy for Inflation. During a period of rapid inflation, a curved balloon grows so large that to any local observer it looks flat. The inset shows the geometry from the ant's point of view.

Grand Unified Theories

While inflation is an intriguing idea and widely accepted by researchers, we cannot directly observe events so early in the universe. The conditions at the time of inflation were so extreme that we cannot reproduce them in our laboratories or high-energy accelerators, but scientists have some ideas about what the universe might have been like. These ideas are called **grand unified theories** or GUTs.

In GUT models, the forces that we are familiar with here on Earth, including gravity and electromagnetism, behaved very differently in the extreme conditions of the early universe than they do today. In physical science, the term *force* is used to describe anything that can change the motion of a particle or body. One of the remarkable discoveries of modern science is that all known physical processes can be described through the action of just four forces: gravity, electromagnetism, the strong nuclear force, and the weak nuclear force ([Table 29.3](#)).

The Forces of Nature

Force	Relative Strength Today	Range of Action	Important Applications
Gravity	1	Whole universe	Motions of planets, stars, galaxies
Electromagnetism	10^{36}	Whole universe	Atoms, molecules, electricity, magnetic fields
Weak nuclear force	10^{33}	10^{-17} meters	Radioactive decay
Strong nuclear force	10^{38}	10^{-15} meters	The existence of atomic nuclei

Table 29.3

Gravity is perhaps the most familiar force, and certainly appears strong if you jump off a tall building. However, the force of gravity between two elementary particles—say two protons—is by far the weakest of the four

forces. Electromagnetism—which includes both magnetic and electrical forces, holds atoms together, and produces the electromagnetic radiation that we use to study the universe—is much stronger, as you can see in [Table 29.3](#). The weak nuclear force is only weak in comparison to its strong “cousin,” but it is in fact much stronger than gravity.

Both the weak and strong nuclear forces differ from the first two forces in that they act only over very small distances—those comparable to the size of an atomic nucleus or less. The weak force is involved in radioactive decay and in reactions that result in the production of neutrinos. The strong force holds protons and neutrons together in an atomic nucleus.

Physicists have wondered why there are four forces in the universe—why not 300 or, preferably, just one? An important hint comes from the name *electromagnetic force*. For a long time, scientists thought that the forces of electricity and magnetism were separate, but James Clerk Maxwell (see the chapter on [Radiation and Spectra](#)) was able to *unify* these forces—to show that they are aspects of the same phenomenon. In the same way, many scientists (including Einstein) have wondered if the four forces we now know could also be unified. Physicists have actually developed GUTs that unify three of the four forces (but not gravity).

In these theories, the strong, weak, and electromagnetic forces are not three independent forces but instead are different manifestations or aspects of what is, in fact, a single force. The theories predict that at high enough temperatures, there would be only one force. At lower temperatures (like the ones in the universe today), however, this single force has changed into three different forces ([Figure 29.27](#)). Just as different gases or liquids freeze at different temperatures, we can say that the different forces “froze out” of the unified force at different temperatures. Unfortunately, the temperatures at which the three forces acted as one force are so high that they cannot be reached in any laboratory on Earth. Only the early universe, at times prior to 10^{-35} second, was hot enough to unify these forces.

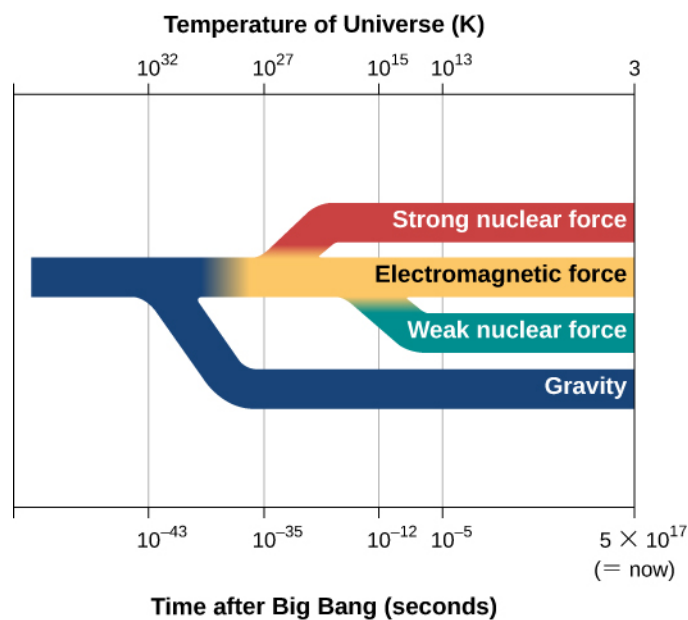


Figure 29.27 Four Forces That Govern the Universe. The behavior of the four forces depends on the temperature of the universe. This diagram (inspired by some grand unified theories) shows that at very early times when the temperature of the universe was very high, all four forces resembled one another and were indistinguishable. As the universe cooled, the forces took on separate and distinctive characteristics.

Many physicists think that gravity was also unified with the three other forces at still higher temperatures, and scientists have tried to develop a theory that combines all four forces. For example, in string theory, the point-like particles of matter that we have discussed in this book are replaced by one-dimensional objects called

strings. In this theory, infinitesimal strings, which have length but not height or width, are the building blocks used to construct all the forms of matter and energy in the universe. These strings exist in 11-dimensional space (not the 4-dimensional spacetime with which we are familiar). The strings vibrate in the various dimensions, and depending on how they vibrate, they are seen in our world as matter or gravity or light. As you can imagine, the mathematics of string theory is very complex, and the theory remains untested by experiments. Even the largest particle accelerators on Earth do not achieve high enough energy to show whether string theory applies to the real world.

String theory is interesting to scientists because it is currently the only approach that seems to have the potential of combining all four forces to produce what physicists have termed the Theory of Everything.^[3] Theories of the earliest phases of the universe must take both quantum mechanics and gravity into account, but at the simplest level, gravity and quantum mechanics are incompatible. General relativity, our best theory of gravity, says that the motions of objects can be predicted exactly. Quantum mechanics says you can only calculate the probability (chance) that an object will do something. String theory is an attempt to resolve this paradox. The mathematics that underpins string theory is elegant and beautiful, but it remains to be seen whether it will make predictions that can be tested by observations in yet-to-be-developed, high-energy accelerators on Earth or by observations of the early universe.

The earliest period in the history of the universe from time zero to 10^{-43} second is called the Planck time. The universe was unimaginably hot and dense, and theorists believe that at this time, quantum effects of gravity dominated physical interactions—and, as we have just discussed, we have no tested theory of quantum gravity. Inflation is hypothesized to have occurred somewhat later, when the universe was between perhaps 10^{-35} and 10^{-33} second old and the temperature was 10^{27} to 10^{28} K. This rapid expansion took place when three forces (electromagnetic, strong, and weak) are thought to have been unified, and this is when GUTs are applicable.

After inflation, the universe continued to expand (but more slowly) and to cool. An important milestone was reached when the temperature was down to 10^{15} K and the universe was 10^{-10} second old. Under these conditions, all four forces were separate and distinct. High-energy particle accelerators can achieve similar conditions, and so theories of the history of the universe from this point on have a sound basis in experiments.

As yet, we have no direct evidence of what the conditions were during the inflationary epoch, and the ideas presented here are speculative. Researchers are trying to devise some experimental tests. For example, the quantum fluctuations in the very early universe would have caused variations in density and produced gravitational waves that may have left a detectable imprint on the CMB. Detection of such an imprint will require observations with equipment whose sensitivity is improved from what we have today. Ultimately, however, it may provide confirmation that we live in a universe that once experienced an epoch of rapid inflation.

If you are typical of the students who read this book, you may have found this brief discussion of dark matter, inflation, and cosmology a bit frustrating. We have offered glimpses of theories and observations, but have raised more questions than we have answered. What is dark matter? What is dark energy? Inflation explains the observations of flatness and uniformity of the universe, but did it actually happen? These ideas are at the forefront of modern science, where progress almost always leads to new puzzles, and much more work is needed before we can see clearly. Bear in mind that less than a century has passed since Hubble demonstrated the existence of other galaxies. The quest to understand just how the universe of galaxies came to be will keep astronomers busy for a long time to come.

3 This name became the title of a film about physicist Stephen Hawking in 2014.