16.4: The Beginning

Learning Objectives

- You will know that the early Universe was extremely dense and that changes happened rapidly.
- You will know that the Planck time is the earliest era we can probe.
- You will know that at the Planck time all four forces are thought to be unified.
- You will know that all of space and time were created in the beginning.

What Do You Think: Beginning of the Universe

16.4.1: Thinking About the Early Universe

Using mathematical models, we can push backward to times of high temperature and density in the Universe, and we can predict what happened within the first moments in its history. Extrapolations like these become less certain the earlier back we go. Eventually, the physics we currently understand need no longer be valid at all. So what can physics tell us, if anything, about conditions at these earliest times?

Two things sometimes bother students when thinking about conditions in the early Universe. One is the extraordinary density at these times. At $t = 10^{-4}$ seconds the density is that of an atomic nucleus. At earlier times, the density would have been higher still. How can anything be denser than an atomic nucleus? The answer is that even atomic nuclei are mostly empty space. We have already looked at the structure of atoms and seen that they consist of tiny nuclei containing protons and neutrons, surrounded by clouds of electrons. The ratio of the volumes of nuclei to atoms exceeds that of a flea to a football stadium. Atoms are almost entirely empty space. But nuclei are themselves also mostly empty space. The protons and neutrons occupy only a tiny fraction of the total volume, and each of them consists of just three quarks inside a volume trillions of times larger—in fact, it could be that the quarks inside nucleons have no well-defined size at all, similar to electrons, neutrinos, and photons.

Perhaps even more difficult to grasp is how it is possible that all the astonishing events we have considered in this chapter occurred in just a few minutes. As we contemplate the entire sweep of cosmic history, it is clear that big changes happened much more quickly at early times, and change has been far more gradual recently. The concentration of events early on is astonishing. However, at those times everything was much closer together and the relative energies and speeds of the individual particles were far higher. Even given that, it is difficult to comprehend how all those events were able to happen so quickly.

If we step back and consider a few common, but quite unfamiliar, timescales, it might help to put this all into perspective.

Our perceptions of the world are limited by our speed of thought, which evolved to allow us to negotiate our everyday world. Thinking is a slow process compared to many of the processes that occurred in the early, hot Universe. In order to think, trillions of neurons, each containing trillions of atoms, have to perform long sequences of complex operations. Thoughts require times of the order seconds to complete. A second is an immensely long time on the subatomic scale. Molecules can vibrate many billions of times in one second. During each single vibration, electrons orbit nuclei perhaps a million times. Protons may orbit the center of a nucleus a million times for each electron orbit. Inside protons and neutrons, the constituent quarks complete a million orbits for each proton orbit. Another way of looking at it is that many elementary particle reactions reach balance (equilibrium) in as little as 10^{-18} seconds. So, for an elementary particle, a second is like many billions of years for a human. There is plenty of time to get things done.

We will now discuss the limits of our current scientific understanding of the early Universe.

16.4.2: The Planck Time

The earliest time we can speculate about is the Planck time. We learned of this timescale already in Chapter 9 when we considered black holes and the failings of general relativity near the singularity at their centers. In Chapter 9 we introduced Planck units as a somewhat crude way to think about such singularities. Planck units are constructed from combinations of physical constants in ways that give characteristic scales (of length, time, mass, etc.) at which we expect quantum effects to be important. One of these was a unit of time given by the expression below.

$$t_{planck} = \sqrt{\frac{hG}{c^5}}$$

In this equation, h is Planck's constant, G is Newton's gravitational constant, and c is the speed of light in vacuum. Numerically, the Planck time is 10^{-43} seconds. On timescales of this size or smaller, the effects of quantum mechanics become dominant. Our classical theories no longer work. When the Universe had an age smaller than the Planck time, we cannot expect any of our physical laws to give us an accurate picture of its behavior. This is because the random effects of quantum physics will completely dominate its dynamics.

We can think of this in another way: We can construct the Planck length, the distance over which a photon could travel in a Planck time.

$$l_{planck} = ct_{planck} = \sqrt{\frac{hG}{c^3}}$$

Numerically, this works out to about 4×10^{-35} m, a tiny distance. When the observable Universe was of roughly this size, quantum effects would have dominated. We are not able to make any predictions regarding its behavior when everything we can see now was compressed into the size of the Planck length.

Thus, the beginning of time and space as we know it starts near the Planck time, $t = 10^{-43}$ seconds. The temperature of the Universe was around 10^{31} K and the density was near 10^{92} g/cm^3. Before this time the known laws of physics break down and time and space have no meaning. As far as we know, this is when time and space began, at least as far as our current conception of them is concerned.

16.4.3: Unification of the Forces

We learned how at a time of 10^{-12} seconds and a temperature of 10^{16} K, the electromagnetic and weak force combined into the electroweak force. We also learned how at a time of about 10^{-35} seconds and a temperature of 10^{27} K, these forces could have merged with the strong force, at least as described by GUT theories. Near the Planck time, we speculate that such high temperatures and densities may have had the effect of unifying all of the four fundamental forces of nature: gravity could combine with the GUT force. Physicists suspect that at the Planck time, all four forces would have been in perfect symmetry, unified in a **Theory of Everything** (ToE). The energies at this stage are far beyond our ability to reproduce in laboratory experiments, so these ideas are highly speculative. Today the strengths of the four forces have a tremendous range—a factor of 10^{38}—but at the extreme temperatures of the Planck time the strengths are expected to converge toward a single value. Figure 16.26 illustrates the time and temperature scales for the unification of the forces.

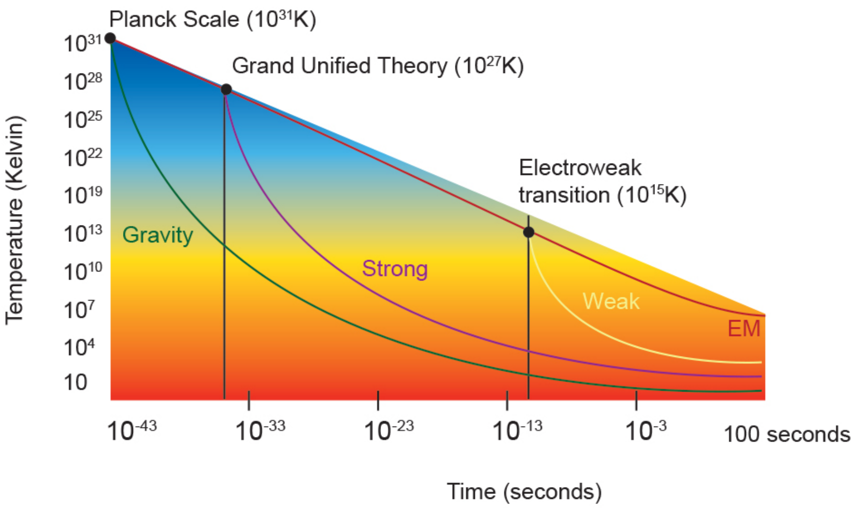

Figure 16.26: Physicists think that all four basic interactions between particles, the electromagnetic, weak, strong, and gravitational, might have all unified as a single interaction in the early Universe. As the Universe expanded and cooled, each force broke off from the others as the energy density in the Universe dropped. First gravity, then the strong interaction broke off. Finally, at 10^{-12} seconds, the weak force separated from electromagnetism, giving us the four interactions we have now. Credit: NASA/SSU/Aurore Simonnet

Much of what we can say about force unification is speculative, but there is some evidence that we are on the right track. We do observe the electroweak unification directly in particle accelerators, and it matches the theoretical predictions very well.

Unfortunately, both the GUT and ToE unifications are well beyond the energy ranges (temperatures) we can produce with current technology. We will have to await future experiments to know if our ideas about times before electroweak unification are correct.

One of the challenges in understanding the ToE unification is that gravity is described by general relativity, whereas the other three forces are described by quantum mechanics. Furthermore, the Big Bang model is built on general relativity. General relativity is what is called a "classical" theory; it takes no account of quantum structure on the smallest scales. We know that on small scales quantum effects dominate the dynamics of the Universe. In the earliest moments of cosmic expansion, the entire observable Universe would have been small enough to be completely dominated by quantum effects—the roiling and bustling of virtual particles popping in and out of existence. What would these effects have done to the Universe when it had a size comparable to these wild quantum fluctuations? To fully answer that question, we need a quantum theory of gravity. Only such a theory will allow us to properly understand the behavior of the Universe at the earliest times. However, a quantum theory of gravity remains elusive.

One way to view the separation of a single force into the four we now experience is as the emergence of the basic laws of nature during these critical early moments. Physicists often consider these laws in terms of what they call invariance or symmetry principles, which tell us whether some property of the Universe is affected by some type of change. Does the behavior change if I do it over there or over here? What if I rotate my perspective? If not, the property is said to have translational invariance, or symmetry, in the first case, and rotational symmetry in the second. If the property appears to operate the same way whether I watch it in normal time sequence or with the ‘film’ played backwards, it has time symmetry/invariance.

Starting in 1915, the German mathematician Emmy Noether (1882–1935, Figure 16.27) demonstrated a fundamental correspondence between such symmetries and the older concepts of conservation laws in physics. Invariance under translation (whether the process occurs over here or over there), for example, requires the law of conservation of momentum. Invariance under rotation requires the law of conservation of angular momentum, and invariance with time implies the law of conservation of energy. There are many quantum symmetries that require other conservation principles (such as those for charge, and the number of various types of particles). Symmetries are an expression of the laws of nature.

Figure 16.27: Amalie Emmy Noether was a German mathematician who made important contributions to topics in algebra and theoretical physics. Her work on symmetries in nature, called Noether’s theorem, showed that such symmetries lead to conserved quantities. Credit: Science Source/Photo Researchers, Inc.

At earlier and earlier times, the Universe was in a sense simpler and simpler. The complexity now expressed in all our physical laws has emerged through a sequence of broken symmetries. They occur naturally as the Universe cools. Physicists suspect that one of them, early on, caused the single ToE force to separate into a GUT force and gravity. Later, when the Universe cooled further, another symmetry was spontaneously broken causing the GUT force to separate into an electroweak force and the strong nuclear force. At that point there were three particle interactions: gravity, the strong, and the electroweak. Finally, another symmetry was broken and the electroweak force became the electromagnetic interaction and weak nuclear interaction that we observe today.

The particular symmetries that were broken in the early Universe have to do with the form of the equations that describe particle interactions, but they work similarly to the way rotation does in mechanics, at least until they are broken. The interactions of gravity in a ToE might be related to a concept called supersymmetry, the idea that for each force carrier particle there ought to be a corresponding mass particle and for each mass particle there should be a force particle.

For example, the fast-moving massless photon, which interacts strongly with matter, would have a slow-moving massive counterpart called the photino. It would not interact strongly with matter. The collection of the massive particles that include the photino are called **weakly interacting massive particles** (WIMPS). They have never been detected, but they represent one possible variety of dark matter.

In this scenario, all but the lightest supersymmetric particle would be unstable. They will have decayed by the present day. The surviving (stable) lightest WIMP is a popular candidate for the dark matter particle that apparently dominates the mass of galaxies and galaxy clusters. The decay of the heavier, unstable WIMPS is analogous to the way free neutrons decay to form more stable protons.

So far supersymmetry is unverified. The lack of success in detecting any of the particles it predicts at accelerators like the LHC have almost ruled it out. Perhaps it is not the correct view of the world after all. But it is just one avenue being explored by physicists as they try to understand matter in its most basic forms.

▼ **GOING FURTHER 16.4:** SYMMETRY BREAKING

16.4.4: The Beginning of Expansion and the Meaning of T = 0

The Planck time is the earliest moment about which we can make scientific statements. But the basic Big Bang theory includes a moment when there was infinite density—a singularity, at $t = 0$. Can we go all the way back to $t = 0$? Whenever a scientific model has a singularity, it is an indication that something is wrong, that the model has broken down and we need something better as we approach the singularity. In the case of our simplest Big Bang model, we know it is failing at $t = 0$.

When thinking about the beginning of the Universe, many people wonder what started it all. That is outside the scope of the Big Bang theory, which describes how the Universe changes *after* the Planck time, through today, and into the future. That is not necessarily a fatal problem. Just as there is a South Pole and nothing further south on Earth, the Universe may have “begun” in a hot, dense state, asymptotically approaching $t = 0$, and there was never any $t < 0$ to worry about.

Georges Lemaître (1896–1966, Figure 16.28) was among the first scientists to argue from the observed Hubble expansion that the Universe must have developed from a super hot, dense era with no obvious antecedent. In fact, he had derived Hubble’s law from general relativity two years before Hubble published his results on the expansion of the Universe. Lemaître called the start of space and time “the day without yesterday.”

Figure 16.28: Georges Lemaître was a Belgian cosmologist - an ordained Catholic Priest who was also a professor of physics. He deduced the cosmic expansion from Einstein's equations of general relativity before Hubble announced his discovery. Lemaître also devised the first theory based on general relativity and the expansion of the Universe that suggested the cosmos originated in a hot, dense state. Image © Shutterstock, Inc.

In this chapter, we have explored the earliest moments of the history of the Universe. The very first seconds of the Universe are not only intrinsically fascinating, they produced many structures that have remained unchanged ever since—like the protons in your body. These early moments began a continuing process of nested structure assembly, permitting more and more complexity—quarks to protons to nuclei to atoms to molecules to living organisms and planets, stars and galaxies. It is because these structures bear the imprints of earlier times that we can make inferences about the Universe's beginnings.

Our current understanding of physics allows us to understand times back to the first trillionth of a second in surprising detail. We can even push back, somewhat tentatively, to times when the Universe was only 10^{-35} seconds old. However, our current state of comprehension does not allow us to probe all the way back to the beginning. We require advances in both theoretical and experimental physics before we can confidently describe the earliest moments. At a minimum, such an understanding requires a more complete knowledge of gravity and its presumed quantum nature on small scales. For the moment, this understanding remains beyond our reach.