universe entered the **grand unified era** (see Chapter 32). There was no distinction between quarks and leptons; baryon and lepton numbers were not conserved. Very shortly thereafter, as the universe expanded considerably and the temperature had dropped to about 10^{27} K, there was another phase transition and the strong force condensed out at about 10^{-35} s after the Big Bang. Now the universe was filled with a "soup" of leptons and quarks. The quarks were initially free, but soon began to "condense" into more normal particles: nucleons and the other hadrons and their antiparticles. With this **confinement of quarks**, the universe entered the **hadron era**.

Quark confinement

About this time, when the universe was only 10^{-35} s old, a strange thing may have happened, according to theorists. A brilliant idea, proposed around 1980, suggests that the universe underwent an incredible exponential expansion, increasing in size by a factor of 10^{40} or 10^{50} in a tiny fraction of a second, perhaps 10^{-34} s. The usefulness of this **inflationary scenario** is that it solved major problems with earlier Big Bang models, such as explaining why the universe is flat, as well as the thermal equilibrium to provide the nearly uniform CMB.† Inflation is now a generally accepted aspect of Big Bang theory.

Inflation

After the very brief inflationary period, the universe would have settled back into its more regular expansion. The universe was now a "soup" of leptons and hadrons. We can think of this "soup" as a grand mixture of particles and antiparticles, as well as photons—all in roughly equal numbers—colliding with one another frequently and exchanging energy.

By the time the universe was only about a microsecond $(10^{-6}\,\mathrm{s})$ old, it had cooled to about 10^{13} K, corresponding to an average kinetic energy of 1 GeV, and the vast majority of hadrons disappeared. To see why, let us focus on the most familiar hadrons: nucleons and their antiparticles. When the average kinetic energy of particles was somewhat higher than 1 GeV, protons, neutrons, and their antiparticles were continually being created out of the energies of collisions involving photons and other particles, such as

Most hadrons disappear

$$\begin{aligned}\text{photons} &\rightarrow \mathrm{p} + \bar{\mathrm{p}}\\ &\rightarrow \mathrm{n} + \bar{\mathrm{n}}.\end{aligned}$$

But just as quickly, particles and antiparticles would annihilate: for example

$$\mathrm{p} + \bar{\mathrm{p}} \rightarrow \text{photons or leptons.}$$

So the processes of creation and annihilation of nucleons were in equilibrium. The numbers of nucleons and antinucleons were high—roughly as many as there were electrons, positrons, or photons. But as the universe expanded and cooled, and the average kinetic energy of particles dropped below about 1 GeV, which is the minimum energy needed in a typical collision to create nucleons and antinucleons (about 940 MeV each), the process of nucleon creation could not continue. The process of annihilation could continue, however, with antinucleons annihilating nucleons, until there were almost no nucleons left. But not quite zero. To explain our present world, which consists mainly of matter (nucleons and electrons) with very little antimatter in sight, we must suppose that earlier in the universe, perhaps around 10^{-35} s after the Big Bang, a slight excess of quarks over antiquarks was formed. This would

Why is there matter now?

†How inflation explains flatness might be understood by thinking of a sphere. If the sphere of Fig. 33–15, with obvious curvature of its surface, were to increase vastly in size, the surface would seem essentially flat to an observer on it. Inflation also explains why the CMB is so uniform. Without inflation, the tiny universe at 10^{-35} s was still too large for all parts of it to have been in contact so as to reach the same temperature (information cannot travel faster than c). Suppose the universe was about 1 cm in diameter at $t \approx 10^{-36}$ s, as per original Big Bang theory. In that 10^{-36} s light could have traveled $d = ct = (3 \times 10^8\,\mathrm{m/s})(10^{-36}/\mathrm{s}) \approx 10^{-27}\,\mathrm{m}$, way too small for opposite sides of a 1-cm-wide universe to have been in communication. But if the universe had been 10^{40} or 10^{50} times smaller, there could have been contact and thermal equilibrium to produce the observed nearly uniform CMB. Thus inflation allows the very early universe before inflation to have been so small that all parts could have been in thermal equilibrium, and after inflation large enough to give us today's universe.