IN THE BEGINNING

The search for the dawn of time

> We aspire in vain to assign limits to the works of creation in *space*…. We are prepared, therefore, to find that in *time* also the confines of the universe lie beyond the reach of mortal men.
>
> – Charles Lyell

In northeastern Arizona, the tributaries of a meandering river known as the Chinle Wash have chiseled out a fan-shaped trio of converging canyons, now protected as part of Canyon de Chelly National Monument. The Chinle Wash flows northward into the San Juan River, which in turn flows westward and empties into the Colorado; some two hundred kilometers to the west, these same waters have carved the gaping chasm of the Grand Canyon. Forged by the same river system, it is not surprising that Canyon de Chelly shares much of the same landscape and geology as its more famous cousin to the west. The trails that zigzag along the southern rim of the Canyon de Chelly system look out over sandstone cliffs that plunge as much as three hundred meters down to the desert floor below; mighty stone pillars like the spectacular Spider Rock leap back up to nearly as great a height. And while the term "off season" barely holds any meaning at the perpetually crowded Grand Canyon, Canyon de Chelly is mercifully quiet. On a recent spring evening, only one other traveler was enjoying the sunset at Spider Rock Overlook – a white-haired gentleman with an enormous 8x10 view camera on a massive wooden tripod, and, for good measure, a Hasselblad on a second tripod. (The equivalent scene at the Grand Canyon, I would discover a few days later, involves hundreds of camera-toting travelers perched shoulder-to-shoulder at just about every accessible spot along the popular South Rim.)

As the sun sinks toward the western horizon, the layers of rock on the northern and eastern canyon walls turn from pinkish brown to luminous orange and red. It is a visual feast – and it also allows one to peer across vast stretches of time. Canyon de Chelly's oldest feature is a layer of sandstone known as the Supai Formation, which formed 280 million years ago – tens of millions of years before the first dinosaurs walked the earth. Above that are the layers that give the cliff walls their warm, rose-colored hue. This is the so-called de Chelly sandstone – former sand dunes, now compressed into solid rock, dating from 250 to 230 million years ago. Some 50 million years later, the uppermost layer, known as the Chinle Formation, was laid down. Of that, only the base layer, known as the Shinarump Conglomerate, remains; the rest has succumbed to millions of years of weathering and erosion.

The rocks at Canyon de Chelly tell a remarkable tale, and time is the central theme in their story. But it has not been easy to decipher the message. It is only in the last few hundred years that we have come to recognize the vast scope of Earth's history, and a parallel discovery – that the entire universe is much older even than these layers of sandstone – is newer still. In ancient times, the vast reach of cosmic history lay hidden.

As we saw in Chapter 4, many ancient cultures envisioned time as a series of endless cycles; in such societies, the question of how or when time began would have been meaningless. "Two thousand years ago," writer Martin Gorst says in his entertaining book *Measuring Eternity*, "the idea that the world might have a starting point was inconceivable." But the idea of a single creation event, first conceived by the Jews (likely borrowing from the Babylonians) and later adopted by the Christians, suddenly made the search for origins a logical quest. For centuries the answer was believed to lie in scripture, rather than in nature – but the search had begun. Great thinkers like Augustine pored over the Book of Genesis, adding up the ages of Adam's male descendants – counting all those "begats" – so as to arrive at the time of the Creation. Augustine ended up with a date of 5500 B.C.; the Venerable Bede, a medieval English monk, had placed it slightly later, at 5199 B.C. Work of this sort continued for a thousand years, into the beginning of the modern era. Kepler, Newton, and Martin Luther all came up with dates in the rather narrow range of 4000 B.C. to 3993 B.C. (The traditional Jewish date of creation is 3760 B.C., although the Hebrew calendar takes as its starting point the previous year, 3761 B.C.)

The Bishop and the Bible

But the most influential statement on the age of the world came from an Irish bishop named James Ussher (1580-1655). Born in Dublin, Ussher was raised as a Protestant in a largely Catholic nation. He had a voracious appetite for books, and read everything in sight; he toured all of the great libraries of Britain and Ireland, and eventually amassed some ten thousand volumes, one of the largest private collections in all of Europe. Ussher looked not only at the Bible but at hundreds of other ancient texts, trying to align the different (and often conflicting) histories that they presented. He eventually pinned down the death of King Nebuchadnezzar II of Babylon to 562 B.C. – a date still accepted by historians. He then went through the Hebrew Bible (the Old Testament), adding up the ages of the prophets and the reigns of the kings until he arrived at Nebuchadnezzar, an interval of 3,442 years. Simple arithmetic then puts the Creation at 4004 B.C. Ussher would go even further, and fix the exact time and date. The apples were ripe in the Garden of Eden, he reasoned, so it must have been fall – likely, he imagined, the autumnal equinox. And since the Genesis account suggests each day began in the evening – “And the evening and the morning were the first day” – he believed the world was created in the evening. He eventually concluded that the world began at 6:00 p.m. on Saturday, October 22, 4004 B.C. Later commentators usually omitted the extra detail, and the first full day, October 23, 4004 B.C., became known as “Ussher’s date.”

Irish bishop James Ussher. His study of biblical chronology led him to believe the world was created on Saturday, October 22, 4004 B.C. *(National Portrait Gallery, London)*

Today we wonder how Ussher could have been so confident in a date that would turn out to be so wrong, and that in any case seems suspiciously precise. But in Ussher's time, many scholars were performing such calculations and obtaining similar results. Most of these studies were forgotten, but the work of this otherwise obscure Irish cleric would become household knowledge. Soon after he wrote his analysis, a London publisher started printing bibles with Ussher's chronology in the margin; in 1701, the Church of England endorsed his timeline in a new translation of the Bible. (As the centuries passed, many readers simply assumed the chronology was *part* of the Bible.) As late as the first decades of the twentieth century, bibles with Ussher's chronology were still being printed.

In the eighteenth century, however, some scholars were beginning to doubt that the earth could be as young as Ussher had proclaimed. A few bold writers openly suggested that Genesis was not an accurate description of how the world began – or, at the very least, that it should be read metaphorically rather than literally.

Among these more adventurous thinkers was a Frenchman named Georges-Louis Leclerc de Buffon (1707-88). In his ambitious *Histoire*

Naturelle, a forty-four-volume work that attempted to cover all of the natural sciences, Buffon argued that the earth was created by a comet hitting the sun. The idea made religious thinkers furious. "In a stroke, he had reduced the creation of the world, the glorious masterpiece of the Supreme Architect, to nothing more than a catastrophic accident," writes Martin Gorst. Buffon also suggested that all species were linked by intermediate gradations, and may have developed from a common ancestor; he believed that God did not concern himself with the details of each plant and animal. As for the biblical account, Buffon said that the language of Genesis had to be carefully interpreted. Echoing the words of Galileo, he said that the Bible had been written not for scientists but for lay readers. There was no need to presume that each "day" mentioned in the opening chapters of Genesis was of the same duration as a modern day of twenty-four hours. Indeed, the very idea of a "day" as a succession of day and night was established only after the third so-called day, with the creation of the sun.

Buffon instead took a scientific approach to calculating the age of the earth. He believed that our planet began as a sphere of molten rock and then gradually cooled down to its present temperature. He began to experiment with balls of different materials, heating them up and then observing how long they took to cool down. After six years of experimentation, he concluded that the earth was 74,832 years old.* He would later work out revised estimates, pointing toward an even more ancient Earth – but these he kept to himself. Perhaps he was taken aback by the large figures he was coming up with and feared that the public would not welcome such information. "Why does the human mind seem to lose itself in the length of time," he wondered. "Is it not that being accustomed to our short existence we consider one hundred years a long time, have difficulties forming an idea of one thousand, cannot even imagine ten thousand years, or even conceive of one hundred thousand years?"

Buffon had based his method on Newton's work on the physics of cooling objects, and Newton had, in fact, used the same technique to estimate the age of the earth. He had come up with a figure comparable to Buffon's – about fifty thousand years. But unlike Buffon, Newton could not accept the figure; it conflicted too sharply with his religious convictions.

Secrets in Stone

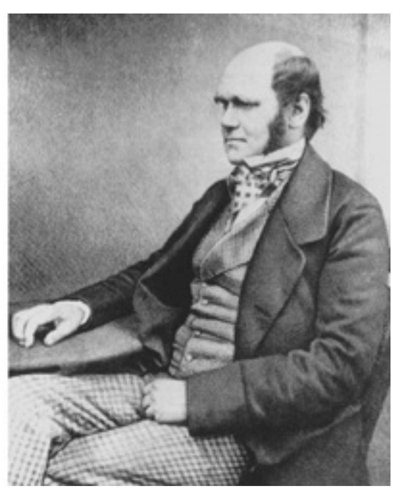
Even in the ancient world, there were some who dared to imagine an evolving Earth, a world whose appearance changed over time. Herodotus, for example, imagined geological processes taking many thousands of years. Around the year A.D. 1000, the Persian philosopher and scientist Avicenna imagined an ancient Earth in terms that sound remarkably modern: mountains, he said, “are effects of upheavals of the crust of the earth, such as might occur during a violent earthquake, or they are the effect of water, which, cutting for itself a new route, has denuded the valleys, the strata being of different kinds, some soft, some hard. The winds and water disintegrate the one, but leave the other intact.” He concluded that it “would require a long period of time for all such changes to be accomplished.”

In the century before Buffon grappled with the age of the earth, the English naturalist John Ray (1627-1705) was examining fossils he had uncovered in the Midlands and northern Wales; some of them, he could see, were of plants and animals that no longer existed. Would it not have taken thousands of years, he wondered, for such species to flourish and then become extinct? If so, it seemed to raise troubling theological questions: If God created a perfect world, why would some creatures die off, to be replaced by others?

Building on Ray’s work, the geologist James Hutton (1726-97) traveled extensively throughout Britain and reached similar conclusions about the age of the earth. He believed that heat from the earth’s interior occasionally pushed molten rock into the planet’s crust, and that rocks such as granite were once molten. Such processes, he reasoned, required enormous amounts of time. “The result, therefore, of our present enquiry,” he concluded, “is that we find no vestige of a beginning, and no prospect of an end.”

For some, this new time scale was impossible to grasp; at the very least, it was difficult to reconcile such vast stretches of time with those mentioned in scripture. But at least one prominent philosopher was ready to embrace this new, longer view. Immanuel Kant (1724-1804) imagined that creation was "not the work of a moment" but rather an ongoing process. In words that seem to presage those of modern cosmologists, he writes, "Millions and whole myriads of millions of centuries will flow on, during which always new Worlds and systems of Worlds will be formed, one after another … It needs nothing less than an Eternity to animate the whole boundless range of the infinite extension of Space and Worlds, without number and without end." As writers Stephen Toulmin and June Goodfield put it in *The Discovery of Time*, "By 1750, men could contemplate a future lasting many thousands of years; but no one before Kant had talked so publicly and seriously of a *past* comprising 'millions of years and centuries.'"

A century later, the geologist Charles Lyell (1797-1875) would conclude that the processes that shaped the earth in the ancient past were the same forces that continue to operate today. Change could come gradually, over thousands of years; cataclysmic events, such as Noah's flood, were unnecessary. Based on the fossil evidence, he concluded that even climates could change over time: Europe, he believed, was once a mild, tropical land. In his *Principles of Geology*, published in three volumes between 1830 and 1833, Lyell reasoned that the earth might be not merely thousands of years old, but perhaps *millions* – a startling claim. It is little wonder that when a colleague gave a copy of the first volume to a young naturalist named Charles Darwin, he urged him to enjoy Lyell's lively writing but to take his conclusions with a grain of salt. Even so, it must have made for provocative reading as the *Beagle* set off on its lengthy voyage.



Charles Lyell (left) was one of the first to suggest that geological processes unfolded over millions of years. Charles Darwin (right) took the first volume of Lyell's *Principles of Geology* with him as he set sail on the *Beagle*. *(Left: Dr. Jeremy Burgess/SPL/Publiphoto; right: SPL/Publiphoto)*

At around the same time, a contemporary of Lyell named George Scrope (1797-1876) was touring France, examining extinct volcanoes. He concluded that they formed gradually, by ongoing geological processes. His conclusion, published in his *Memoir on the Geology of Central France* (1827), is perhaps the most famous utterance ever delivered by a geologist: "The sound which, to the student of Nature, seems continually echoed from every part of her works, is – Time! – Time! – Time!"

Darwin's Deep Time

Charles Darwin (1809-82) was fresh out of university and thinking about training for the priesthood when one of his teachers suggested he take passage on the HMS *Beagle* as the ship's naturalist. The aim of the voyage was to conduct hydrographic surveys of the coast of South America, as well as the islands of the South Atlantic and eastern Pacific. The *Beagle* set sail in 1831 on a journey that was supposed to last two years but that in the end lasted five. On the long voyage, Darwin saw ample evidence of geological forces at work; in just the first few months, he was converted to Lyell's view of an ancient Earth. Darwin observed coral atolls, which he deduced were formed by volcanoes now vanished. In the Cape Verde Islands, he saw cliffs apparently thrust upward by a succession of volcanic events. In Chile, he witnessed an earthquake. He reasoned that the Andes themselves were formed by gradual geological upheaval. It was as though Lyell, in spirit, was on the deck of the *Beagle* alongside Darwin. The geologist's book "altered the whole tone of one's mind," he would later write. "When seeing a thing never seen by Lyell, one yet saw it partially through his eyes."

And then there were the animals. Darwin did not immediately know what to make of the great variety of species that he saw. On the

Galapagos Islands alone there were dozens of different species of finch, each differing from the others only by slight variations in the size and shape of their beaks. Fossils, meanwhile, showed that species that had once flourished were now extinct, while new species had come to take their place. Here he would come to disagree with Lyell, who held to the notion that each species, once created, never changed.

Darwin's ideas about evolution began to take shape only after his return to England in 1836. After living briefly in London, he moved to a large country home southeast of the city. He married his first cousin, Emma Wedgwood (of the porcelain dynasty), and fathered ten children, seven of whom survived to adulthood. For the next two decades, he pored over his notebooks, studied his specimens, and considered what he had seen on his voyage. (At the same time he was battling a crippling illness, suffering constantly from vomiting, shivering, palpitations, and headaches. The illness was never diagnosed. Whatever it was, it often left him too sick to work; on his good days he was lucky to work for even a few hours.)

Darwin was not the first to speculate about evolution; in fact, his grandfather, Erasmus Darwin, had suggested that all warm-blooded animals had arisen from a common ancestor. But the question of *how* species changed over time was still unresolved. Charles Darwin's breakthrough was not the idea of evolution itself but the mechanism behind it: *natural selection*. (Roughly put: organisms that are best adapted to their particular environments are more likely to survive and reproduce, passing on whatever traits gave them an "edge" to their offspring.) This mechanism of natural selection was the tool that nature used to create new species of plants and animals. Evolution demanded time – and Darwin believed that, thanks to Lyell's geology, there was more than enough to go around. Darwin did not discover "deep time," but, standing on the shoulders of the geologists, he wholeheartedly embraced it. "What an infinite number of generations which the mind cannot grasp," Darwin wrote, "must have succeeded each other in the long roll of years."

On the Origin of Species was published in November 1859. The first edition sold out immediately, and ran through six more editions in the next dozen years. The scientific community was swift to embrace

Darwin's ideas. There were, of course, theological objections: Darwin's theory suggested that all living things were related – he would later write that men and apes are essentially cousins – and because all species evolve gradually, no special "act of creation" was required.* These were difficult ideas to get used to; some conservative religious thinkers were never able to accept them. And looming over the entire debate was the vast evolutionary timeline. Ussher's chronology, with its six-thousand-year age for the earth, began to seem quaint. Our planet's history, and life itself, now seemed irrevocably to stretch back millions of years. "Darwinism," as writer Timothy Ferris has put it, "was a *time* bomb."

The impact of this revolution in our conception of time, which had gained almost universal acceptance by the end of the nineteenth century, was eloquently expressed by the geologist Archibald Geike: "How vast a period must have been required for that marvelous scheme of organic development which is chronicled in the rocks!" he declared in 1892. "The law of evolution is written as legibly on the landscapes of the earth as on any other page of the book of Nature." That evolution is revealed both in the living world and in the planet itself:

> The living plants and animals of to-day have been discovered to be eloquent of ancient geographical features that have long since vanished … They tell us that climates have changed; that islands have been disjoined from continents; that oceans once united have been divided from each other, or once separate have now been joined … The present and past are thus linked together, into one vast system of continuous progression.

Darwin himself was awed by the ageless drama of evolution – and the vast epochs of time it demanded. As he wrote in *Origin*, "He who … does not admit how vast have been the past periods of time may at once close this volume."

The conclusions reached by the geologists and naturalists would soon be shared by the physicists. The discovery of X-rays in 1895 and of radioactivity a year later would open up a new world within the atom – and yield new tools for probing vast stretches of time. The New Zealand-born chemist Ernest Rutherford (1871-1937), working in Montreal, discovered that certain elements were unstable and released energy at an ever-decreasing (but predictable) rate, for prolonged periods of time. Minerals that contained those elements could release energy for thousands, even millions, of years. Rutherford immediately recognized the importance of his discovery: the earth's interior isn't simply getting cooler over time, as Buffon had assumed two hundred years earlier; instead, it is being continuously heated from within, by the decay of radioactive elements in the planet's molten core. Radioactivity "thus increases the possible limit of the duration of life on the planet," Rutherford wrote, "and allows the time claimed by the geologist and biologist for the processes of evolution."

The concept of radioactive decay would lead to a powerful new technique for determining the age of minerals. The rates at which these unstable particles decay are independent of changes in temperature and pressure, depending only on the particular element involved. Before long, geologists were using the new method of "radiometric dating" to measure the ages of rocks now revealed to be hundreds of millions of years old. In his book *The Age of the Earth* (1927), physicist Arthur Holmes declared, "All the evidence is consistently in harmony with the conclusion … that the age of the earth is between 1,600 and 3,000 million years" – that is, 1.6 to 3 billion years.* The age suggested by Ussher, and by now usually associated directly with the Bible, suddenly seemed like a drop in the vast ocean of geological time. "For a public used to dealing in everyday numbers of tens and hundreds," writes Martin Gorst, "this huge jump, from millions to billions, was dazzling."

Dazzling, yes – but fortunately for scientists, such numbers are no harder to manipulate than those one can count with one's fingers. We may not be able to picture these large numbers – it is hard enough to "see" fifty thousand fans in a packed sports stadium – but that does not get in the way of using such figures. Arthur Eddington, the British astronomer – he led one of the eclipse expeditions that confirmed Einstein's general relativity in 1919 – understood this paradox of large numbers. In a popular essay, he tabulated, in kilometers, the distances to the sun, the nearest star, and various other astronomical objects, out to the furthest galaxy known at the time, given as 3,000,000,000,000,000,000,000. "Some people complain that they cannot realize these figures," he writes. "Of course they cannot. But that is the last thing one wants to do with big numbers – to 'realize' them. In a few weeks time our finance minister in England will be presenting his annual budget of about £900,000,000" – this was in the days when national budgets were *less* than a billion pounds or dollars. "Do you suppose that by way of preparation, he throws himself into a state of trance in which he can visualize the vast pile of coins or notes or commodities that it represents? I am quite sure that he cannot 'realize' £900,000,000. But he can spend it." Such large numbers "are not meant to be gaped at," Eddington says, "but to be manipulated and used."

Time and the Cosmos

The stars, too, tell a story that revolves around time – and this story, like the story of Earth's ancient origins, took centuries to interpret. While every culture had myths about how the universe began, the scientific study of cosmology is actually one of the youngest of the sciences; in its modern form, it began only in the first decades of the twentieth century. Although Galileo had seen that the fuzzy band of light called the Milky Way is really a vast collection of stars – far too many for him to count – it took more powerful telescopes, and more sophisticated new techniques for determining the distances to the stars, to reveal our galaxy's true structure. We now know that it is shaped like a giant Frisbee, some 100,000 light-years across,* with a bulge in the middle and spiral arms sweeping out to the edges. (From our perspective, embedded inside one of the spiral arms, it appears as the milky band that we see at night.) With the advent of larger telescopes, astronomers began to catalog other fuzzy patches of light, known as nebulae, seen scattered across the heavens. Some of them were observed to have distinctive spiral shapes; these at first were known as "spiral nebulae," but by the 1920s it was clear that they were galaxies like our own. These "external" galaxies were similar to the Milky Way, but incredibly distant. (In fact, Kant had suggested as much in the 1750s, referring to such nebulae as "island universes.") Our picture of the cosmos was growing.

But that was just the beginning. Astronomers were learning how to measure the distances to those galaxies, and by looking at their spectra, they could calculate the speed at which they were moving through space. The spectral lines of many galaxies were found to display a shift toward the red end of the spectrum – a *redshift* – suggesting they were moving away from our own galaxy. (The phenomenon is analogous to the "Doppler effect" that makes the siren of a receding ambulance sound lower in pitch than it does when stationary.) Then, in 1929, the American astronomer Edwin Hubble (1889-1953) made a remarkable discovery. Hubble had been using the hundred-inch telescope at Mount Wilson in California – at that time, the largest telescope in the world – to systematically study distant galaxies, which he found "scattered through space as far as telescopes can penetrate." To his great surprise, he found a correlation between a galaxy's distance from the Milky Way and its motion: the farther the galaxy, the faster it was speeding away. He had discovered the expansion of the universe.

Hubble's new picture of the cosmos was a radical one. Until then, there had been no reason to imagine that the universe was anything but *static* – that it had always been there, and that it had always looked pretty much the way it looks now. The new picture was far more dynamic. We live in an evolving universe.

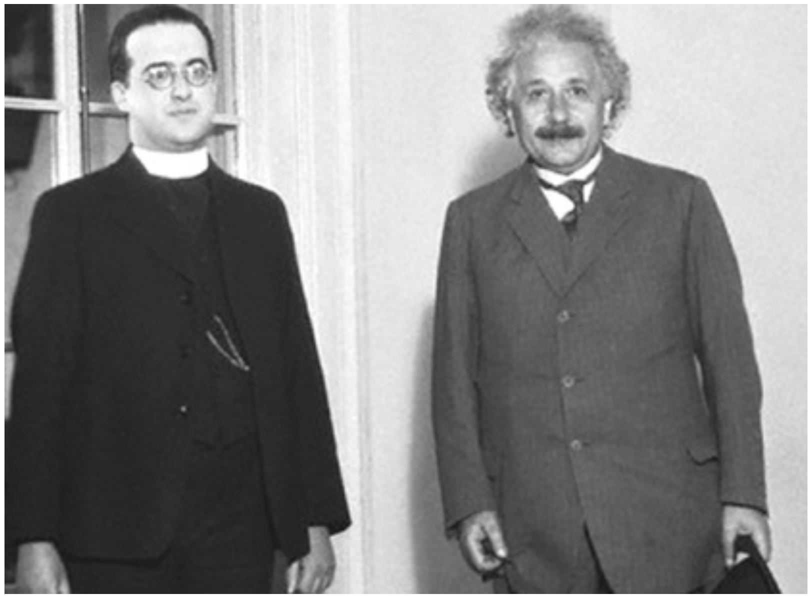
U.S. astronomer Edwin Hubble. His study of galaxies beyond the Milky Way showed that we live in an expanding universe. *(Hale Observatories / SPL / Publiphoto)*

Interestingly, the expansion of the universe was almost anticipated by Einstein. Just a few years after he worked out his equations for general relativity, he began applying them to the universe at large. But he was surprised by what they implied: the equations did not seem to allow a static universe; instead they appeared to demand that the universe must be either expanding or contracting. A handful of scientists were willing to explore such scenarios; the Russian cosmologist Alexander Friedmann, for example, found solutions to Einstein's equations that suggested an expanding universe, which he considered a perfectly reasonable scenario. A Belgian physicist named Georges Lemaître, who was also a Catholic priest, went further; even before Hubble announced his finding, Lemaître suggested that the observed redshifts could be a sign of the universe's expansion, and put forward the idea that the world began as a "primeval atom."*

Einstein would have none of it. Like the vast majority of scientists at the time, he believed in an unchanging universe. He went so far as to introduce a fudge factor into his equations, known as the *cosmological constant*, to "balance" the universe. Just a few years later, however, came Hubble's monumental discovery – and Einstein immediately regretted his cosmic fudge. He called it the "greatest blunder" of his career.

The Expanding Universe

The implications of an expanding universe are staggering. Wind back the clock, and the universe gets smaller. If you go back far enough, it must have been incredibly tiny. Before long, the notion of a cosmic explosion had taken root: the universe must have started off as an incredibly dense, hot fireball. As it expanded, it cooled. (Today, we're lucky to be living near a nice warm star, because the average temperature of the universe is just a few degrees above absolute zero – more than 270 degrees below zero on the Celsius scale.) As the universe cooled, the first structures formed, leading, after billions of years, to the universe we see today, peppered with galaxies and clusters of galaxies. Astronomers call this the *big bang* model of the universe.* (The name was coined by the astronomer Fred Hoyle during a 1950 BBC radio broadcast. Ironically, Hoyle rejected the theory in favor of his own ill-fated “steady state” model.)



Belgian priest and physicist Georges LeMaître (left), one of the originators of the “big bang” model of cosmology. Albert Einstein at first could not accept the idea of an evolving universe. *(Caltech Archives)*

The work of Hubble and Einstein led to a new world view. The universe, it seemed, now had a beginning. (To some scientists, the big bang model smacked of Christian theology – and it didn’t help that one of its originators was an ordained priest.) It now appeared as though time itself began at a precise moment, and, suddenly, it seemed within the bounds of science to determine when that momentous event happened. The quest for the beginning of time, which had started with the rocks underfoot, had moved into the heavens.

By the middle of the twentieth century, the evidence for the big bang was beginning to mount. Physicists learned how to measure the abundance of the chemical elements that make up the stars and galaxies, and it turned out that the amount of hydrogen, helium, and heavier elements was just what the big bang model predicted; the numbers were consistent with the notion of an expanding and cooling cosmic fireball. The icing on the cake, however, came in the mid-1960s. The clearest "fingerprint" of the big bang turned out to be a kind of echo of that initial explosion – not an echo of sound, but an echo of microwave radiation, discovered by accident in 1965 by two scientists using a giant radio antenna in New Jersey. Arno Penzias and Robert Wilson detected a faint microwave signal coming from every direction in the sky. They had discovered the signature of the big bang, now known as the "cosmic microwave background," or CMB. (By coincidence, at around the same time, physicist Robert Dicke and his colleagues at Princeton University – just an hour away – predicted the existence of the CMB based on theoretical models of the big bang. They were preparing to search for such radiation when they heard of the discovery by Penzias and Wilson.) One can think of the CMB as a splash of radiation that was released when the universe was less than half a million years old; today this radiation fills all of space. Penzias and Wilson received the Nobel Prize in 1978 for their discovery.

More recently, scientists have used a satellite known as WMAP – the Wilkinson Microwave Anisotropy Probe, launched in 2001 – to examine the background radiation in detail. With the data from WMAP, astronomers have been able to describe the basic features of the universe with remarkable precision. We now know, for example, that the universe is "flat," meaning that it can be described by the simple geometry of Euclid: parallel lines remain parallel, and the three angles of a triangle add up to 180 degrees. We also know that "ordinary matter" – stars and planets, for example – accounts for just 4 per cent of the contents of the universe. (Of the remainder, mysterious "dark matter" makes up about 23 per cent, and the even more mysterious "dark energy" accounts for 73 per cent. We will hear more about dark energy in the next chapter.) Finally, WMAP has let scientists pin down the age of the universe: astronomers now believe the big bang happened 13.7 billion years ago – give or take a couple of hundred million years.

The Ultimate Free Lunch

The discovery of the cosmic microwave background was an enormous breakthrough, but it also raised new questions. For one thing, the universe is awfully big – much bigger than physicists would have expected based solely on the big bang model. Also, the radiation was very "smooth" – that is, astronomers measured exactly the same intensity of microwave radiation no matter which direction they aimed their telescopes. (No part of the cosmic background radiation deviates from the average by more than a few parts per million.) If the universe were small, that wouldn't be so surprising: information could have passed back and forth from one part to another, smoothing everything out. But the universe is big – and it's only been around for 14 billion years. There just hasn't been enough *time* for this smoothing out to happen, across such large distances.

A tentative solution came in the early 1980s, when cosmologists came up with a modified version of the big bang picture, known as "inflation." According to inflation, the universe went through a period of incredibly rapid expansion during its first split-second of existence. This period of rapid (or "exponential") growth helped to explain why the universe is so large and so smooth. Several scientists worked on inflation, but the first crucial paper was written by physicist Alan Guth (now at MIT) in 1981. Guth's model doesn't specify exactly what was driving the inflation process. Physicists call the responsible entity a "scalar field" because it can be described by a single number attached to every location in space, rather like temperature – though this hardly helps us picture what is doing all of that pushing. But the inflation model appears to work: it successfully describes the subsequent evolution of the universe.

Inflation, incidentally, also gives us another dose of Copernican-style humbling: it suggests that the portion of the universe we can see with our telescopes – vast as it is – is just a small fraction of the larger cosmos. The visible universe (sometimes referred to as our "bubble" or "horizon") is surrounded by more distant regions – but these have been pushed away so rapidly by inflation in the universe's earliest moments that light from such regions has not had time to reach us. These far-off realms may remain forever unknown to us, as there is no way to receive any kind of signal from them.

Scientists are not used to the idea of something being created from nothing; even Aristotle shuddered at the idea, believing it an affront to reason. And yet the inflationary universe seems to entail just that. If the theory is correct, writes Alan Guth, "then the inflationary mechanism is responsible for the creation of essentially all the matter and energy in the universe." The origin of matter, he says, is no longer beyond the reach of science. "Conceivably, everything can be created from nothing … In the context of inflationary cosmology, it is fair to say that the universe is the ultimate free lunch." Inflation quickly became the "new and improved" big bang; it is now considered a standard part of the description of cosmic evolution. And, remarkably, all of the observations that astronomers have carried out so far appear to support the theory. (For example, inflation predicts the universe to be geometrically "flat," as WMAP has confirmed.)

At a recent conference on inflationary cosmology held in Davis, California, I asked Guth – mild-mannered, friendly, and eager to discuss his work – to give me the beginner's guide to inflationary cosmology. "Inflation is a twist on the big bang theory," he explained. "Inflation is an answer to the question, 'What caused the universe to propel? What triggered this gigantic expansion, that we're still seeing the universe undergoing?'" According to inflation, Guth explains, the scalar field exerted an enormous pressure on all of the matter in the universe. The universe ballooned in size, doubling in diameter again and again, a hundred times over. Before inflation, the universe was more than a billion billion times smaller than a proton; after inflation, it was about the size of a marble (or perhaps a grapefruit) – and it all happened in a tiny fraction of a second. With a steady stream of observational data from WMAP and other studies of the CMB appearing to support inflation, Guth says he has just as much confidence in the theory today as he did in 1981. "I think the observations certainly show that either inflation is right, or something that's very close to inflation is right, and explains how the universe got to be the way it is."

That is not quite the end of the story: cosmologists have come up with other scenarios that challenge the inflation model, and we will look at those shortly. Our picture of the origin of the universe will surely continue to evolve as bigger telescopes and more sophisticated theories reach deeper into the cosmos than we can peer at present. Our generation is not the first to believe it has nailed down the story of how the universe began, or even to pinpoint its age. As Martin Gorst reminds us, Ussher was not the only one who came up with the wrong answer. "Many of the greatest minds in science were equally blinkered, trapped by their own beliefs, or the prevailing assumptions of their day." Newton failed to take the idea of an ancient Earth seriously, and for many years Einstein balked at the idea of an expanding universe. Even geniuses can be led astray.

In the medieval world, people imagined a relatively short cosmic time scale, compatible with the view that the universe was made *for us* – a view that persisted well into the beginning of the modern era. The much longer timeline revealed by geology and later by cosmology was humbling; human beings appeared to play a much less central role in cosmic affairs. As Timothy Ferris has put it, "The larger the universe looms, the sillier it becomes to maintain that it was all put together for us." Nor is our location particularly special: we live on a typical rocky planet orbiting an average yellow star that lies partway out along a spiral arm in a very ordinary galaxy that we call the Milky Way. But from this outpost we have learned how to observe the greater cosmos, and for the first time we have data – real data from telescopes on the ground and in space – that reveal the structure and history of our universe with remarkable clarity. In that respect, modern cosmology is not "just another creation story," as some postmodernist scholars suggest. There are, of course, many more details to be worked out, but in its broad outline, we can be confident in the big bang model of the evolving universe. The universe as we know it – and time as we know it – began 13.7 billion years ago.

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* Like Ussher's date, Buffon's estimate seems overly precise. He does not seem to have worried about his "margin of error."

* Darwin would address the issue of human origins directly in his later book, *The Descent of Man*, published in 1871.

* The modern value is about 4.5 billion years, based on the oldest known rocks, meteorites, and

lunar samples.

* A light-year is the distance that light travels in one year – roughly 9.5 trillion kilometers.

* Although Hubble is generally credited with discovering the expansion of the universe, several other scientists, including astronomers Vesto Slipher and Milton Humason, made important contributions. The work of Lemaître was largely ignored at the time, in part because he published in a relatively obscure Belgian journal. Many now consider Lemaître the “father of the big bang.”

* Although I’ve used the word “explosion” in describing the big bang, the term can be misleading. Physicists think of the big bang as an expansion of space itself, rather than an expansion of matter *into* a preexisting space. For this reason, there is no one “place” where the big bang happened, nor must the universe have an edge. Nonetheless, the universe may be finite, just as the surface of an expanding balloon is finite.

BEYOND THE BIG BANG

The frontiers of physics and the origin of time's arrow

> Our picture of physical reality, particularly in relation to the nature of *time*, is due for a grand shake-up – even greater, perhaps, than that which has already been provided by present-day relativity and quantum mechanics.
>
> – Roger Penrose, *The Emperor's New Mind*

The big bang model of our cosmic origins must be counted as one of the great triumphs of twentieth-century science. In its latest incarnation – the theory of cosmic inflation – it allows us to grasp a period beginning a billionth of a trillionth of a trillionth of a second after the big bang (or, put more succinctly via scientific notation, 10^{-33} seconds after the birth of the universe). The model gets us tantalizingly close to the beginning. Yet the story is still frustratingly incomplete. After all, the most interesting question that we can ask is not what was happening some tiny fraction of a second after the big bang, but rather, can we turn the clock all the way back to "time zero"?

That last step is a big one. How did time begin? What, if anything, was going on *before* the big bang? Does it even make any sense to ask that question? Physicists and cosmologists are used to hearing the issue raised. At the end of countless public lectures on cosmology, someone in the audience invariably comes up to the microphone, thanks the speaker for an insightful talk, and then asks, "So, what happened *before* that?" For many years, the question was simply considered off limits to science. Physicists and cosmologists, it was suggested, could probe what came *after* the big bang but were powerless to probe the actual origin of the universe; the matter was better left to philosophy or religion. Many physicists, meanwhile, argued that the big bang marked the beginning of time, so there simply was no such thing as "time" beforehand. The question of what happened before the big bang then becomes meaningless, just as one cannot meaningfully say what lies north of the north pole.

Our quest to understand that first moment is thwarted on several fronts. To begin with, our theoretical tools are inadequate. Gravity is the force that governs the expansion of the universe, and we understand gravity reasonably well, thanks to Einstein's general relativity. But gravity by itself will not be enough to probe the universe's earliest moments. The equations of general relativity tell us that at the moment of the big bang everything in the universe would have been *infinitely* squeezed together; the universe would have been compressed into a single point. In the jargon of mathematical physics, such a point is known as a "singularity." To a physicist, singularities are about as welcome as the plague. A theory that describes the real world shouldn't have such mathematical kinks, they reason, and so a model that predicts the existence of singularities is treated with suspicion. We will ultimately need not only general relativity but also quantum theory, the theory of the very small. Perhaps when these two ways of describing the world are brought together, in the long-sought theory of quantum gravity, the infinities will disappear, and we will have a coherent picture of the beginning of time.

One suggestion, put forward by Stephen Hawking and U.S. physicist James Hartle, uses quantum theory to blur time and space together, on a microscopic scale, at the moment of the big bang. Known as the "no boundary" proposal, it eliminates the problem of the singularity by "smearing out" time's origin. (Hawking gives an outline of the proposal in Chapter 8 of *A Brief History of Time*, for those who made it that far.) In this model, although time does not stretch indefinitely into the past, it also has no sharp beginning. Time does not suddenly "switch on" but rather emerges gradually from space.

For now, the no-boundary proposal remains just that – a proposal. So far, a full-fledged theory of quantum gravity – at least, one that everyone can agree on – does not exist. Of the various efforts to achieve such a framework, the front runner is *string theory*, an ambitious attempt to unify gravity with the other forces of nature.* In the string picture, the most fundamental "bits" of matter are not particles, but rather tiny loops of string. Because the strings have a finite size, the problem of infinite compression – those pesky singularities – is avoided. And the theory does seem to give a quantum description of gravity. But string theory actually gives physicists more than they asked for: it seems to indicate that we live in a world of more than three dimensions (more accurately, three dimensions of space and one of time). In fact, it says we might live in a world of ten or eleven dimensions.

The idea of extra dimensions sounds bizarre at first, but string theorists take it quite seriously. The latest ideas about the role that such dimensions might play in our universe come from a recent spin-off of string theory known as M-theory (where M stands for "membrane"). According to M-theory, in addition to one-dimensional strings, the universe is also made up of membranes with two or more dimensions.

The Universe on a Brane

We will not examine M-theory in detail, but it is worth mentioning that, in the last few years, physicists have begun to develop cosmological models based on the remarkable framework suggested by the theory. In some of these scenarios, our universe – everything we can see through our largest telescopes – might just be a kind of three-dimensional "slice" of some higher-dimensional structure. In the jargon of M-theory, we may live on a "brane" (short for "membrane"). (For a comparison, think about your own shadow: when you look at the ground on a sunny day, your shadow is just a two-dimensional slice, so to speak, of your three-dimensional body.)

These brane-world models offer a startling new description of the cosmos. In some scenarios, the entire visible universe is merely a three-dimensional membrane – called a "3-brane" – embedded in a larger structure, known as the "bulk." This larger structure must have at least four space dimensions – and, as usual, one more for time. The remarkable thing about these brane models is that there's no reason to presume that our universe is unique: there could be any number of "parallel" universes – parallel branes – sitting alongside ours in the four-dimensional bulk. Even Hawking, once a skeptic, now seems to back the brane-world idea. At the conference in Davis, he said, “I must admit I have been reluctant to believe in extra dimensions, but the M-theory network fits together so beautifully, and has so many unexpected correspondences, that I feel to ignore it would be like claiming that God put fossils in the rocks to trick Darwin into believing in evolution.”

One of the pioneers of brane-world cosmology is Paul Steinhardt of Princeton University. Steinhardt was one of the first people to work on the inflation theory, but in the last few years he’s focused much of his energy on exploring these brane-world models of the cosmos. One particular model that he developed, in collaboration with Neil Turok (now at the Perimeter Institute) and several other colleagues, offers an entirely new view of the big bang. There are two actually two versions of this idea, known as the “ekpyrotic” and “cyclic” models. Both of them describe the big bang as a collision between two of these branes. The big difference is that in the cyclic model, such collisions can happen again and again. The result is multiple big bangs, leading to a potentially endless series of universes.

After a very full day at the Davis conference, I sat down with Steinhardt in his hotel room, where he tried to help me picture these new models of the universe. “You should imagine that there’s a force between these two 3-dimensional worlds that would tend to draw them together, as if they were two rubber sheets being drawn together by a spring,” he said. “And at regular intervals they would come together, smash together, creating a certain amount of heat – which we would think of as being radiation and matter – and then bounce apart again.” In other words, if we lived on one of those branes, we would have the impression that there was a massive burst of energy in our past – which is, in fact, what we perceive. In the cyclic version, he explains, the “bounce” is both an ending and a beginning – the end of one “universe” and the beginning of another, as it enters a new phase of expansion and cooling. “Now we begin the cycle anew,” Steinhardt says. “We have the universe filled with hot matter and radiation, we form new stars, new galaxies, new planets, presumably new life – and the cycle continues.”

As I tried to wrap my brain around these branes, I reminded myself that Steinhardt's proposal is more educated speculation than testable theory – at least for now. But if the cyclic model is correct, it clearly says something quite profound about both space and time. The theory "raises the basic issue of whether time has a beginning at the moment of big bang," Steinhardt says, "or whether the big bang is instead really a transition to an earlier epoch of evolution."

Steinhardt's brane-world cosmology is not the only attempt to reach beyond the big bang. Guth's inflation theory has evolved, and in one intriguing version, it, too, attempts to describe a larger cosmos. The idea is that the inflation process could have spawned more than just one universe – a model sometimes called "eternal inflation." The most prominent supporter of this view is Andrei Linde, a Russian-born physicist now at Stanford University. Linde believes that whatever caused that period of inflationary growth could have given rise to many – perhaps an infinite number of – separate universes. The cosmos as a whole, Linde speculates, may be immortal. For his part, Guth seems to relish this new, "bigger" version of inflation. And he admits that it would be "clearly an oversimplification to view the big bang as being the beginning of time."

Before the Beginning

These competing visions of our cosmic origins, speculative as they are, must be admired for at least attempting to probe the physics of the early universe beyond the moment of the big bang. They also challenge the imagination as much as anything science has offered. In fact, just about *any* theory of how the universe began necessarily presents such a challenge. We struggle in vain to imagine time stretching back to infinity – but we find it is just as difficult to imagine that time had a beginning.

Part of the problem is that our intuition tells us that every event had a cause; every "happening" is the result of some earlier happening that gave rise to it. And yet quantum mechanics has already shown that some events, such as the decay of a radioactive nucleus, just "happen." Perhaps the universe – along with space and time – did, roughly speaking, pop into existence from nothingness. As physicist Edward Tyron has put it, "Our universe is simply one of those things which happen from time to time." If that picture is correct, then Augustine was on the right track when he declared that God created time and the world together; before that, time simply did not exist.

In contemplating time's origins, our intuition can take us only so far. We're used to dealing with space on the scale of meters and kilometers, and we're used to dealing with time on the scale of seconds and days and years. On these human scales, time seems quite well behaved. Words like "before" and "after" seem perfectly clear in their meaning, while time, like space, seems smooth and uniform – so much so, that we sympathize with Newton and his claim that time "flows uniformly." But Einstein, as we've seen, has already shown us that under certain circumstances, time can behave in much stranger ways. Add to that the shadowy world of quantum mechanics, and we are left with a hint of where physics may be heading.

Physicists hope to one day have a unified theory that reaches beyond both relativity and quantum theory – and when they do, time might not be a part of it. As physicist Lisa Randall has written, we are finding "tantalizing hints of space breaking down at short distances and time breaking down at singularities"; these apparent breakdowns "tell us that fundamentally, space and time are not what we think." Indeed, many physicists now routinely speak of time and space emerging from something – no one can quite say *what* – at the moment of the big bang.

Making Time (Out of Nothing at All)

The idea of "emergent time" is embraced by some of today's brightest young researchers. Among them is Nima Arkani-Hamed, who, at age thirty-six, recently left a tenured position at Harvard to join the faculty of the Institute for Advanced Study in Princeton, New Jersey. "We don't know what happened at the big bang," Arkani-Hamed admits. "But one thing we know for sure is that the whole idea of space and time breaks down – so the idea of what came 'before' may not even make sense." We are "clearly missing something very big," he says – and that something "is certain to involve the idea of emergent time."

Time, in other words, may not be a fundamental part of our universe. Just as the wetness of water emerges from the bulk properties of billions of water molecules sliding past one another, so time itself may emerge from some more fundamental “stuff,” whatever that stuff may be.

Exactly *how* time emerges remains to be seen. Time seems to get treated differently depending on whether one starts with general relativity and then tries to add quantum theory, or whether one starts with quantum theory and then tries to add general relativity. (In string theory, which takes the latter approach, physicists usually have to “insert” time and space by hand. They would ideally like to find a “background independent” version of the theory that might actually explain the emergence of space and time based on the vibrating strings or membranes that lie at the heart of the theory.)

David Gross, a particle physicist and string theorist based at the University of California at Santa Barbara, believes the idea of emergent time is something we may simply have to get used to. Gross, who shared a Nobel Prize in 2004 for his work on quarks and the strong nuclear force, believes that the quest for a “unified theory” is leading us toward a picture in which time may no longer be fundamental. “Time is really built in deeply to the way we think about physics, and so is space,” he told me recently. “But we’ve learned in many cases that space is sort of an emergent concept. There are realms of string theory that are best formulated in terms of concepts that don’t involve space at all. We have no such examples involving time – but since space and time are so connected in our understanding, it’s hard to imagine that if space is an emergent concept, that time wouldn’t be as well.” This would change, among other things, the way we think about the beginning of the universe. “The idea of time ‘flowing’ from the beginning until now is an approximation,” he says. “It might be a very good approximation to describe the evolution of the universe after a few seconds, but not before.”

I press him on the question of what came before the big bang. “There are only three possibilities that I can think of,” he says. “One is that, through quantum mechanics, the universe emerged out of nothing. Or else there was something there before. Or else you change the question – which is my favorite,” he says. In other words, time “is an emergent concept that doesn’t make any sense under those circumstances. So these are the three possibilities that I can see. And, who knows?”

It’s only natural for theorists at the frontiers of physics to push ahead with all manner of avant-garde ideas, from string theory to brane-world cosmology and beyond. Yet without grounding in experiment, such musings can only go so far. One of the frustrating things about cosmology, of course, is that one cannot repeat the experiment: the big bang happened once – at least, one time that we can be sure of – and we have to make do. But while scientists can’t recreate the big bang, they are hoping to do the next best thing: at a massive new particle accelerator near Geneva, Switzerland, physicists are trying to reproduce the intense temperatures and energies that prevailed in the earliest moments of the universe. The $10-billion project is called the Large Hadron Collider, or LHC, and it was nearing completion just as this book was going to press.

A lot is at stake at the LHC. Experiments at the collider could hint at how the forces that we see today were unified in the remote past. They could reveal exotic properties of matter like “supersymmetry,” and may shed some light on the dark matter that makes up much of the universe. We may also get a glimpse of the extra dimensions beyond the three dimensions of space that we’re familiar with; if such evidence is found, string theory may not seem like such a stretch of the imagination after all. And then there’s the “Higgs boson,” the particle believed to be responsible for mass. (The Higgs is thought to generate a field, analogous to an electromagnetic field, which in turn makes other particles seem heavy.) Many physicists are confident that the LHC will finally snare the Higgs, jokingly referred to as the “God particle.”

Of course, it will take months – even years – to wade through the data once the machine is up and running, and there are many different kinds of experiments to perform. But most scientists seem confident that the LHC will finally provide answers to some of the deepest problems in physics – perhaps even illuminating the difficult issue of the emergence of space and time. “We’ll have something to say by 2010,” asserts Arkani-Hamed.

The Arrow of Time Revisited

Physicists struggle not only with the question of how time began, but also with the equally vexing problem of how it came to have a *direction*. We have already looked at the "arrow of time" in connection with entropy and the second law of thermodynamics – but the second law, as we've seen, seems to provide only a partial explanation for time's elusive flow.

The thermodynamic arrow of time points from order to disorder, from low entropy to high entropy, from teacups to shattered china. But time's arrow also reveals itself in other ways. In fact, scientists have noted at least six different (though perhaps related) "arrows of time." Beginning with the one just mentioned, they are:

• *The thermodynamic arrow of time*

The second law of thermodynamics says that the amount of dis order in a closed system must increase over time. Typical examples include the breaking of an egg, the mixing of coffee and cream, or the melting of a block of ice – but the same principle is borne out when we observe any complex process in nature.

• *The radiative arrow of time*

Think of a rock thrown into a pond: the impact creates circular ripples in the pond's surface, and these ripples move outward from the point of impact, in circles of ever-increasing size. We do not see the reverse process: we do not see slight distortions at the edges of ponds slowly moving toward each other, gaining strength and speed, until they converge at a spot in the middle of a pond, causing a rock to be ejected upward from the pond's surface. But the equations work either way: the mathematical description we use to analyze the waves does not indicate a preferred direction for their motion.

It is not just water waves that display this preference. Maxwell's equations describe the propagation of electromagnetic waves – but again, they do not tell us which way the waves will move. (For example, they would be equally valid in describing light waves coming together from deep space to merge at a camper's flashlight, rather than the reverse.) In physics, the normal forward-in-time propagation of waves that we see in nature is said to produce “retarded waves” (because they arrive late, so to speak), while the reverse scenario involves “advanced waves” (which, if they existed, would arrive early). The advanced waves are allowed mathematically but never seem to occur. As with the thermodynamic arrow, probability appears to play a role: the chances of those ripples from the sides of the pond coming together “just so” would be staggeringly unlikely. Indeed, such a wave would cause the entropy of the system to decrease (as would an advanced electromagnetic wave). Because of this connection, some physicists believe the radiative arrow can be explained by means of the thermodynamic arrow.

• *The quantum arrow of time*

As we saw in Chapter 7, quantum mechanics may provide yet another arrow of time: when a quantum system is observed, the wave function of the system is said to “collapse” from a superposition of many states into a single state. This collapse appears to be irreversible, suggesting a link to the direction of time. It is not clear how this arrow may relate to the others, although some have speculated on a link between the quantum arrow and the thermodynamic arrow.

• *The kaon arrow of time*

Just about every subatomic process that we know of is, in principle, reversible; the mathematical descriptions of the behavior of the particles involved indicate that they can “go” either way, with no preferred direction in time. But there seems to be one peculiar exception – a particle known as the “neutral k-meson,” or “kaon.” (There are also positively charged and negatively charged versions of the particle.) The neutral kaon is unstable; it quickly decays, usually into a similar kind of subatomic particle called the “pion.”

The decay process, governed by the “weak” nuclear force, can go both ways; that is, physicists can smash pions together to create kaons. But there is a difference: the reaction used to produce kaons takes just a trillionth of a trillionth of a second (10^{-24} seconds), but the decay takes longer – up to a nanosecond (10^{-9} seconds). Why should the decay of a kaon take a thousand trillion times longer than its creation? (As Paul Davies remarks, it is "rather like throwing a ball in the air and finding it takes a million years to come down again.") The kaon's peculiar inclination to "play by its own rules" is deeply puzzling, and there is no obvious connection between this "kaon arrow" (sometimes known as the "weak interaction arrow") and the other arrows of time. (Even so, the significance of this arrow is disputed. Brian Greene, for example, has said that the behavior of kaons is "likely to be of little relevance" to the arrow of time.)

• ***The cosmological arrow of time***

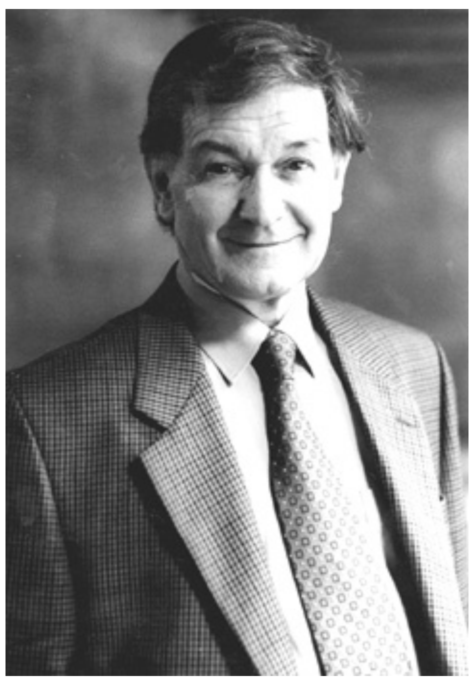
The universe has been expanding ever since the moment of the big bang, about 14 billion years ago. Many physicists would say that this defines a "cosmological arrow of time" – one direction points to our hot, dense past; the other, to our cool, sparse future.

As we've seen, some physicists suspect a link between the cosmological arrow and the thermodynamic arrow, as both seem to be the result of the peculiar conditions that prevailed in the early universe; we will look at this more closely in a moment.

• ***The psychological arrow of time***

Finally, there is the arrow of time suggested by our direct experience, based on our perceptions of the world: we remember the past but not the future; we experience – or seem to experience – a "flow" of time in a unique direction. When the brain is thought of as an information-processing system – a set of correlations between the billions of neurons that make up the brain – a link is suggested, perhaps, between the psychological arrow and the thermodynamic arrow. (Hawking, for one, supports this view.)

Physicists (as well as philosophers and psychologists) have spent years grappling with the question of how these seemingly unrelated arrows of time may be connected. Probably no one has considered those connections more deeply than Oxford mathematical physicist Roger Penrose. Described recently by *Discover* magazine as a "polymath extraordinaire," Penrose first made a name for himself through his work on black holes. In the 1960s, in collaboration with Stephen Hawking, he showed that the collapse of a massive star would inevitably lead to a singularity, and that a singularity must be surrounded by an "event horizon" – the zone surrounding a black hole from which nothing can escape. He has also developed a novel description of spacetime known as "twistor theory," which suggests that space and time are "quantized" rather than continuous – that is, both space and time are made up of discrete chunks – and that those chunks can be described by means of imaginary numbers (such as the square root of –1).* Penrose has also made contributions to pure mathematics: in the 1970s he proved that one can cover a flat surface with tiles in such a way that the pattern you create never repeats itself, even if your tiles come in just two different shapes; this was previously thought to be impossible. These are now called "Penrose tiles."**



Physicist Roger Penrose. *(Courtesy of Jerry Bauer)*

The Singular Scientist

I remember seeing Penrose in action for the first time in the spring of 1990. I was still in journalism school at the time, and Penrose was in town to give a public lecture at the University of Toronto. I vividly recall his use of overhead projection sheets – already somewhat “old-school” at that time. The diagrams and text were done by hand with thick colored marker. There were spacetime diagrams, cartoon-like alive-and-dead cats, and somewhat intimidating rows of equations; each sheet was a little more challenging than the one before. He talked about Gödel and Plato, computers and algorithms, brains and minds. In the lobby after the talk, I bought a copy of his just-released book, *The Emperor’s New Mind*. The book – described as “brain-aching” by the *New York Times* – kept me occupied through much of the following summer. His latest book, a 1,100-page tome titled *The Road to Reality: A Complete Guide to the Laws of the Universe* (2004), is even heftier.

Over the years, I’ve had the chance to speak with Professor Penrose, now in his mid-seventies, on several occasions, most recently on a visit to Oxford in the spring of 2007. Arriving early, I take a stroll through the triangular-shaped park across from the Mathematical Institute. At one end is a small parish church dedicated to St. Giles. Everything in Oxford seems to speak across the centuries, and St. Giles does not disappoint. A plaque on the wall lists all of the vicars going back to 1226. In the park there’s a small graveyard. Some of the tombstones are so weathered as to be completely illegible. Beyond the graves, at the tip of the triangle, there’s a war memorial; locals sit on the lower tiers of the monument to eat their lunches, talk on their cell phones, and enjoy the May sunshine. Between the graveyard and the memorial there’s a spherical bronze sundial – which reminds me it is time to go inside.

Some leading physicists, should they happen to stray off campus, could pass for lawyers or accountants (or in a few rare cases, rock musicians). Not Roger Penrose. Wearing a navy blue sweater and a tweed jacket, he looks like the very definition of “long-tenured theoretical physicist.” For a professor, though, his office at the Mathematical Institute is unusually tidy, with books and journals arranged in neat rows and stacks. On his desk I notice two cardboard boxes filled with the Penrose tiles that he invented thirty years earlier. One set is an amusing variation known as “Penrose chickens.” Think of it as a jigsaw puzzle containing two kinds of shapes – fat chickens and thin chickens. Penrose licensed the design to a company that specializes in mathematical puzzles and games, which crafted them using thick, brightly colored sheets of plastic. Penrose periodically picks up a chicken, or casually slides one around on the desk, as we begin to talk about the nature of time.

We start with the arrow – or rather arrows – of time. Penrose assures me that they are real. The flow of time is another matter; that may well be in our heads. In *The Emperor's New Mind*, he writes, "We *seem* to be moving ever forward, from a definite past into an uncertain future … Yet physics, as we know it, tells a different story." And later, in his second popular book, *Shadows of the Mind* (1994): "According to relativity, one has just a 'static' four-dimensional space-time, with no 'flowing' about it. The space-time is just *there* and time 'flows' no more than does space." But the appearance of an arrow of time – that is, a unique "directionality" associated with that apparent flow – is real enough, he says. The various arrows are the result of physical phenomena that we can observe and measure. "Many of them are related to each other – [although] not always terribly simply," he says. Some of them, such as the arrow of time suggested by the decay of the kaon, are "still very puzzling." The psychological arrow, too, is so far unexplained. Even though *Shadows of the Mind* dealt with the problem of consciousness, he admits we do not yet have enough of a grip on the problem to make much headway. "Remembering the past rather than the future – I don't think we understand enough about consciousness to say too much about that," he says.

One area where we have made progress is with the thermo dynamic arrow; it is certainly the arrow that Penrose has studied most intensely. As we saw in Chapter 6, however, the origin of the thermodynamic arrow of time presents somewhat of a mystery. The second law of thermodynamics tells us that if we currently have a low-entropy system, we can expect to have a high-entropy system in the future – but it does not tell us where the present low-entropy state came from. Can it ultimately be traced back to the origin of the universe itself? Perhaps the origin of the thermodynamic arrow of time lies in the nature of the big bang.

A Very Special Big Bang

"We really have to go back and look at initial conditions," Penrose says. "The second law of thermodynamics tells us – in very sort of commonplace terms – that things get more random as time goes on." But as you look back to earlier and earlier times, this leads to a problem. "It tells you that as you go back in time, things get less and less random" – that is, they become more and more ordered; the entropy decreases. But, Penrose explains, this seems to be at odds with our observations, which suggest just the opposite. Our clearest picture of the early universe comes from the cosmic microwave background radiation (the CMB, which we looked at in Chapter 9). Data from the WMAP satellite and other observations of the CMB show that the initial fireball was actually incredibly "smooth." In the jargon of physics, it was in a state of "thermal equilibrium" – that is, every part of that microwave glow is at almost exactly the same temperature as every other part. If we accept Penrose's line of reasoning – and not all physicists do – then the early universe must have been in a state of very *high* entropy – just the opposite of what we would have expected based on the second law.

"Thermal equilibrium is the maximum entropy state," Penrose says. "In other words, it's the most completely *random* state you could be looking at. Now, this would seem to be a blatant paradox."

Penrose seems genuinely troubled – to the extent that one can be troubled by events that happened 14 billion years ago. He leans back in his chair, his right elbow on the desk. From time to time he picks up a Penrose tile and flips it about. Then he leans back even farther. "I don't know why people haven't worried about this more," he says.

Penrose thinks he knows where we've been led astray: we have failed to take into account gravity. Only when we incorporate gravity into our picture of the early universe, he argues, will we come to understand the roots of the second law of thermodynamics.

When we talk about entropy in everyday situations, we can safely ignore gravity. Usually, we can readily see what's in equilibrium and what isn't. (Think of milk thoroughly mixed in a cup of coffee; the molecules simply can't *be* any more random, so we're confident in saying it's in equilibrium.) At first glance, a perfectly smooth entity like the CMB would also seem to be in equilibrium. But gravity changes things. Although the reasons are rather technical, once we take gravity into account, a perfectly smooth entity like the CMB might actually be seen as being very far from equilibrium – and thus very *low* in entropy.

Penrose concludes that the gravitational field of the early universe was not in equilibrium at all; in fact, he says, "it was very, very special" – and by "special" he means it was in a highly ordered state. How special? At this point, Penrose takes the conversation in what seems like a new direction: he begins to discuss the entropy of black holes. It may sound as though he has gone off topic, but he has not: the big bang and black holes are in some ways very similar, at least mathematically. In one case, matter emerges from a singularity; in the other, matter evolves *into* a singularity. (However, they are not quite mirror images of each other: Penrose cautions that "the singularities in black holes don't look the remotest bit like the big bang in reverse time." I decide to take his word on this.) Fortunately, we do know something about the entropy of black holes – Stephen Hawking and physicist Jacob Bekenstein showed how to work that out in the 1970s – and we can use the same approach for the early universe, Penrose says.

"We can now estimate how special that initial state was," he says. "And it's fantastically special – very, very extraordinarily special. If you just take into account the part of the universe we see, the probability of that initial state having arisen purely by chance is less than 1 part in 10 to the power 10 to the power 123" – that is, 1 part in $10^{10^{123}}$. (This number is so large – a one followed by 10^{123} zeros – that we could not write it out even if we attached a zero to every atom in the known universe.) "Now, that's ridiculously special," Penrose says. "So, there is a huge puzzle there, which cosmologists hardly ever address – and I find this very strange." Even the theory of cosmic inflation, which explains several other problems associated with the physics of the early universe, "does not explain that initial very special state," he says.

Is there any way out of this conundrum? Ultimately, Penrose says, any attempt to develop a unified theory of physics will have to take all of this into account. Indeed, such a theory may have to have some kind of time-asymmetry built into it, he says – which would make it radically different from the laws of physics that we have developed so far. ("I've been saying this for decades," Penrose says, looking more detached than weary. "People listen to me, maybe even nod their heads – then they go off and do the same quantum gravity they've been doing before. They barely pay any attention to this.")

Of course, Penrose is the first to admit that his own approach to quantum gravity is not particularly orthodox: he feels that quantum theory as it currently stands is incomplete, so just trying to "quantize" gravity (Einstein's general relativity) will not work. Penrose does not have the answer, though he would obviously be pleased if twistor theory, or something like it, proved to be on the right track. But he does have his suspicions: he wouldn't be surprised if the time-asymmetry of the "collapse of the wave function" in quantum mechanics turns out to be connected to the time-asymmetry inherent in the second law of thermodynamics – that is, he suspects a link between the quantum arrow and the thermodynamic arrow. "I also believe – and this is a little bit more far out – but I also believe it's got something to do with our perception of the passage of time."

Mind and Matter

Penrose has come up with some unorthodox ideas over the years, but he is always very conscious of what constitutes mainstream science and what does not. He readily admits when one of his ideas rests more on conjecture than on established theory. Now that we are beginning to wade into the prickly question of human consciousness, he knows we are crossing into the realm of speculation. "Does consciousness have anything to do with this? This is where I'm a little more far out on the fringe, to say that, yes, it probably has got something to do with it."

He wonders in particular about the connection – if there is one – between the thermodynamic arrow of time and the psychological arrow. Memory, of course, seems to be intimately connected to time. Yet it operates in just one direction: we remember the past but can only imagine the future. The second law of thermodynamics, meanwhile, seems to work the other way around. If you see an ice cube sitting on the kitchen counter, you know that in a few minutes there will just be a puddle of water. But if someone comes in a bit later and sees only the puddle, they would have no way of knowing where the water had come from. You can't "retrodict" the presence of the ice cube.

"Retrodiction is terrible – normally," says Penrose. "That's what the second law is telling you. Yet remembering is *what we do*. We retrodict with our minds all the time." Ultimately, he says, thermodynamics can offer only limited insight into our mental conception of time's passage. "There isn't a clear statement to say, 'Okay, it's the second law of thermodynamics.' That's no answer. There's something much more subtle going on … It has to do with awareness, it has to do with consciousness. It has to do with issues we're very far from understanding."

As for time itself, Penrose stops short of offering a definition. "I really don't know," he says. "I certainly would say that time is not what we think it is. It's not a sort of steady progression – certainly not a sort of universal steady progression."

It is telling that physicists find it easier to say what time isn't than to say what time is. It isn't merely a steady flow, it isn't just an increase in disorder, it isn't simply the reflection of an expanding universe. After speaking to so many scientists, it's beginning to seem as though the only universally-agreed-upon statement one can make about time is that it's not what we think it is.

Even when we do seem to have some particular aspect of time nailed down – such as the "arrow of time" identified by Eddington more than eighty years ago – it threatens to slip from our grasp. Thermodynamics seems to illuminate one facet – but only one facet – of time's arrow. We now know that there are many "arrows of time," and even today's brightest minds cannot say precisely how they are related. Perhaps time is less like the singular flow of the Nile and more like the multiply-branching Amazon – or the chaos of a Los Angeles freeway interchange. Or maybe no metaphor is quite powerful enough to capture time's essence.

* A more detailed look at string theory can be found in Chapter 7 of *Universe on a T-Shirt*.

* As odd as it may seem to the nonspecialist, physicists often make use of imaginary numbers, which have proven to be particularly useful in solving problems in electromagnetism and quantum theory.

** It turns out that Penrose tiles have practical applications: in physics, they describe a kind of crystal known as a "quasicrystal."

ALL THINGS MUST PASS

The ultimate fate of life, the universe, and everything

Perceivest not
How stones are also conquered by Time?
Not how lofty towers ruin down,
And boulders crumble? Not how shrines of gods
And idols crack outworn?

– Lucretius, *On the Nature of Things*(1st century B.C.)

Eternity is very long, especially toward the end.

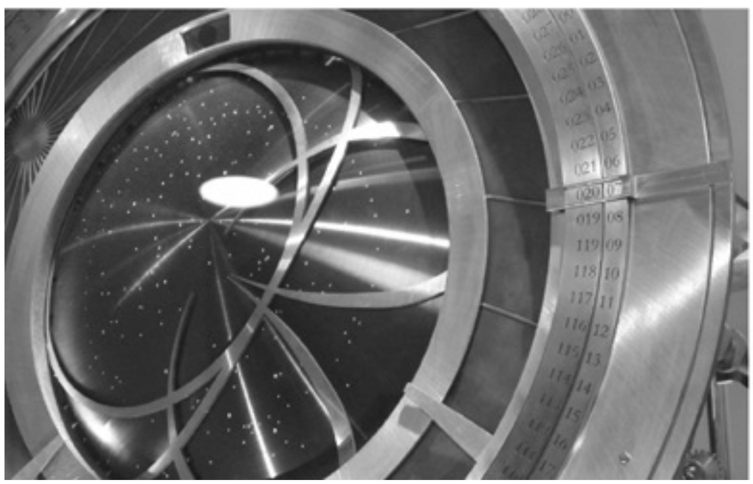
– Woody Allen

The city of Oxford is known for many things – its “dreaming spires,” as a poet once described it; its storied quadrangles, honey-colored walls, and graceful arches; its throngs of tourists. The well-preserved college buildings are beautiful and ornate – and of course old. So old, the guidebooks remind us, that names like “New College” can be misleading: the college was founded in 1379, when the university itself was already a couple of centuries old. There is a wonderful story about the wooden roof of the college’s dining hall. In the middle of the nineteenth century, the massive oak beams that support the roof had to be replaced. The warden and his team of carpenters promptly went out to the forests owned by the college and cut down mighty oak trees that had been planted five hundred years earlier – just a few years after the founding of the college – for that very purpose.

The story may be slightly exaggerated – apparently oaks are typically harvested after 150 years, not 500 – but it is still an inspirational story of long-term planning of the sort rarely seen in the frantic bustle of today’s world. One of those touched by the story was Danny Hillis, an American inventor and scientist known for his pioneering work with supercomputers. Hillis began to reflect on humanity’s short-sightedness, and considered different ways to encourage long-term thinking. Eventually he decided on a machine: he vowed to build a clock that would run for 10,000 years. Hillis, who once ran the research and development department of Walt Disney Imagineering, teamed up with a group of like-minded thinkers who shared his vision of “deep time.” The group came to include Kevin Kelly, the founding editor of *Wired* magazine, and Stewart Brand, creator of the Whole Earth Catalog, who once said that “civilization is revving itself into a pathologically short attention span.” The group established the Long Now Foundation, and their planned clock has been dubbed the Clock of the Long Now. (The name comes from British avant-garde musician Brian Eno, who coined the phrase “long now” after a visit to New York. The right-here, right-now perspective of New Yorkers struck him as radically different from the longer view taken by Europeans. “I came to think of this as ‘The Short Now,’ and this suggested the possibility of its opposite – ‘The Long Now,’” Eno has written. “‘Now’ is never just a moment. The Long Now is the recognition that the precise moment you’re in grows out of the past and is a seed for the future.”)

Embracing the Long Now

The long-term plan is to build this great chronometer in the Nevada desert, where Hillis’s foundation has already bought a seventy-five hectare plot. The clock, they imagine, will be a towering structure, perhaps twenty-five meters in height, and will be built to endure through the ages. That project is still in the planning stages, but a more modest prototype, just three meters high, has already been built. The device was assembled at the group’s workshop in northern California, and now rests in the Time Gallery in London’s Museum of Science. It is an appropriate home. On the gallery’s upper level is a staggering array of clocks and watches from across the ages, from a replica of an Egyptian shadow clock dating to around the ninth century B.C. to the first cesium atomic clock, built in 1955. But the Long Now clock does not resemble any of these.



The prototype of the Clock of the Long Now. The clock is designed to keep time for 10,000 years – note the five-digit display for the year. *(Photos by author)*

"It doesn't really look like what you would expect a clock to look like," says Alison Boyle, the museum's curator of astronomy and modern physics. As we approach the clock's glass-walled display case, it looks like some kind of top-heavy, one-eyed metal creature. The giant black "eye," about half a meter across, is the clock's dial, which displays just about everything except for hours and minutes. ("Hours are an arbitrary artifact of our culture," Hillis says.) Instead it shows a rotating star field designed to reflect the motions of the real sky, displaying the phase of the moon and the position of the sun, even taking into account the 26,000-year precession cycle of the equinoxes.* An outer dial displays the Gregorian year, shown as a five-digit number; 2007, for example, is shown as 02007. “The idea is, obviously, that it will be going for 10,000 years, so we need to avoid a ‘Y10K’ problem,” says Boyle.

Even in the subdued light of the museum, the device gleams; its various parts are made of brass, stainless steel, tungsten, and a nickel-copper alloy that goes by the trade name of Monel. Yet in some ways, the clock is very old-school: there are no electronics; the power comes from falling weights, just as it did in the first mechanical clocks that started to appear in England’s cathedrals in the thirteenth and fourteenth centuries. The clock “ticks” twice a day, the motion of its gears regulated by a device known as a “torsional pendulum.” The three-pronged pendulum, supporting three massive tungsten spheres, rotates back and forth in a horizontal plane at the bottom of the machine. Above the pendulum is a complicated-looking device known as a “binary mechanical computer” (also called a “serial bit adder”) that controls the display on the dial; its shape is suggestive of records stacked in a jukebox, or perhaps a pile of metallic pancakes suitable for an android’s breakfast. Of all the artifacts in the museum, Boyle says, the thing it most closely resembles are the designs of nineteenth-century computer pioneer Charles Babbage; indeed, the Long Now clock has been dubbed “the world’s slowest computer.” Actually, it is hard to pin down just what era the Long Now machine belongs to: one imagines it was put together by Leonardo da Vinci, using spare parts from the *Millennium Falcon*.

From its desert home, the full-scale version of the clock will read the sun’s passage across the sky, automatically remaining in sync with respect to solar time over the millennia. In this respect it is again a throwback to designs of past centuries, when clocks would be corrected, manually, to match the readings of a sundial. Yet the Long Now clock would not be self-sustaining: it would need to be “wound” – a deliberate attempt to turn its caretakers into active participants rather than passive observers. One of the aims is to foster a sense of stewardship and responsibility. Indeed, its parts may need to be periodically replaced.

Already the London prototype has “become a symbol for a whole new way of thinking about time," says Boyle. "The idea behind this clock is not only that it keeps time, but it actually encourages us to change the way that we think about time, and how we measure it."

The prototype was completed late in 1999, and "ticked" for the first time at midnight on December 31 of that year, ushering in the new millennium.* It then started the third millennium with two rings of its one-thousand-year chime. Members of the Long Now team imagine the full-scale version accompanied by a library, with a digital archive of texts in a thousand languages – another attempt to communicate across the ages.

One can think of the Clock of the Long Now as a temporal analog of the brass plaques that accompanied the *Pioneer* spacecraft that traversed the outer solar system in the 1970s – the first purpose-built human artifacts destined to leave the solar system. The plaques, which depict a naked man and woman, data about the solar system, and music from Chuck Berry and others, were designed to communicate across vast distances; should they one day be intercepted by intelligent aliens, the plaques would tell them quite a bit about the civilization that sent them (including, if they had the right sort of record player, what we liked to dance to). The Clock of the Long Now is designed to communicate across time. The challenge is similar – very similar, in fact, because the *Pioneer* craft are moving so slowly that by the time they are discovered (in itself a long shot), millions of years will likely have passed. A ten-thousand-year clock forces us to ask what future civilizations will be like. Will human beings millennia from now resemble us in any recognizable way? Will they think and act the way we do? Will they value what we value?

Peering into the future is like straining to see through a thick fog; nearby objects can be seen, at least in rough outline; more distant landscapes are lost in the mist. Time obscures the view.

In the physical realm, the next few moments may seem clear enough – a falling hammer will hit the ground, a rainstorm will eventually peter out. But as soon as we try to make specific predictions about complex systems – and that would certainly include human affairs – we see how limited our powers of foresight are. We know the future will bring both death and taxes, but we cannot say who will die when (probably for the better), or precisely how much tax we will pay a few years down the road.

We can be more confident in the broad brushstrokes than in the details. Population forecasters, for example, can look at fertility rates and predict that the world's population will peak at about 9 billion by 2070 before beginning to fall. We can be certain that most of that growth will take place in developing countries, and that more and more of the world's population will live in cities (more than 60 per cent by 2025, according to UN projections).

Trying to imagine specific events is far tougher. We may be reasonably certain that 2018 will see both a World Series and an Academy Awards ceremony – but what about 2518? There will presumably be a U.S. federal election in 2040 – but what about the year 3000, or 10000? The weekly newsmagazines routinely run cover stories like "Your Life in 2020," looking a decade or so into the future – but who, other than science-fiction writers, really gives any thought to what civilization might be like a thousand years from now? Or a million? The farther ahead we look, the murkier it all becomes. While the past seems etched in stone, the future is a blur of infinite possibility. If the Clock of the Long Now survives ten thousand years – roughly the length of time from the Agricultural Revolution until now – who will gaze upon it?

A Brief History of the Future

Trying to forecast the future is a relatively new pastime. There were, of course, religious texts that made such predictions – although works like the Book of Daniel in the Hebrew Bible and the Book of Revelation in the New Testament also served to deliver more urgent messages about the eras in which they were written. In the sixteenth and seventeenth centuries, the first utopian worlds were imagined – notably in Thomas More's *Utopia* and Francis Bacon's *New Atlantis*. The sixteenth-century French apothecary Nostradamus published collections of prophecies, predicting various kinds of natural disasters along with wars and military invasions – all of them vaguely worded, undated, and open to endless interpretation. Also in France, some two hundred years later, a collection of long-term predictions appeared in a book called *L'An 2440,* published in 1770 by dramatist Louis-Sébastien Mercier. The book tells the story of an eighteenth-century Frenchman who falls into a deep sleep and awakens seven centuries later. He discovers that in the twenty-fifth century, war has been nearly eliminated and slavery has been abolished. France is still a monarchy, but its population has grown by half, and Paris has been rebuilt on a scientific plan. A canal has been built through the Suez, and balloons (!) offer rapid transport from one continent to the next.

Predictions of this sort become more common in the nineteenth century. (By the end of that century, the genre we now call science fiction was beginning to flourish.) One example, again from France, comes from a series of colorful cigarette cards printed in 1900. Commissioned as part of the *fin de siècle* festivities held throughout the country, the cards depict life "*en l'an 2000*." (The illustrations were reprinted in Isaac Asimov's *Futuredays* in 1986.) The whimsical drawings depict all manner of airships and lightweight wooden flying machines – all rather flimsy-looking to the modern eye. Personal flying devices seem to be ubiquitous, though they appear to be little more than canvas or fabric wings that attach to the body; presumably the wings flap to provide lifting power.

It seems as though the artist has taken the technology of 1900 and attempted to extrapolate it into the future – and yet has missed nearly all of the great technological developments of the century that lay ahead. Aviation did, of course, blossom – but thanks to the jet engine and lightweight aluminum alloys, our planes typically carry many people (often hundreds), and do so primarily over long distances. Personal flying devices have not been realized, and most short-distance travel is accomplished by automobile at ground level. The artist also clearly imagined a progression of bigger and better airships – and yet, even before the fiery explosion that destroyed the *Hindenburg* in 1937, the airship was on the way out.

There were many who believed that heavier-than-air flying machines would never succeed. In 1895, Lord Kelvin – at that time, President of the Royal Society – called such craft "impossible"; a few years later, the Canadian-born astronomer and mathematician Simon Newcomb declared, "Flight by machines heavier than air is unpractical [*sic*] and insignificant, if not utterly impossible." The Wright brothers took flight at Kitty Hawk just eighteen months later.

In the twentieth century, the most famous bad predictions seem to involve the computer. In the 1940s, the chairman of IBM suggested that the worldwide market for computers could just about be counted on one hand. And in 1977, Ken Olson, the president of Digital Equipment Corp., said, "There is no reason anyone would want a computer in their home." (The Commodore PET, the Tandy Corporation's TRS 80, and the Apple II were all introduced that very year, and, for better or for worse, people have been hunched over their home computers ever since.) Just a few years later, in 1981, Bill Gates is said to have declared that "640,000 bytes of memory ought to be enough for anybody."

One could go on endlessly with examples of "bad predictions"; the Internet is full of them. Predicting the future – and the future of technology in particular – is a multifaceted challenge. Often the importance of new materials (plastics, aluminum, steel) is not foreseen. Sometimes a new technology – even if it builds on advances that have come before – can seem utterly novel (as with the Internet). Even when a discovery or invention is already upon us, there can be a kind of ripple effect of unimagined consequences. When the first Model T rolled off the Ford assembly line in 1908, who could have foreseen freeways, traffic jams, suburban sprawl, the rise of the shopping mall (and the decline of "Main Street"), grievous air pollution, or global warming? Sometimes change happens faster than we could have imagined; sometimes much slower – as with those flying cars and robotic servants that always seem to be just a decade away, and yet never quite materialize.

A Word from the Futurists

It will be interesting to see if today's generation of futurists fare any better. Science-fiction author Arthur C. Clarke, who died in early 2008, has a mixed record. In a 1971 short story, he placed the first manned mission to Mars in 1994; by 1999 he was more cautious, admitting that "we'll be lucky to make it by 2010." With just two years to go, it seems unlikely we will make it by then, either. (The consensus these days is more like 2050 to 2080.) But Clarke also had some major successes: he predicted the use of communications satellites in geosynchronous orbits, as well as the so-called millennium bug (which, happily, turned out to be fairly benign when the computer clocks rolled over on January 1, 2000).

Some of Clarke's more recent predictions were relatively modest – Prince Harry will become the first member of the royal family to fly in space – while others were more exotic. He expected that, by the end of the century, we'll have a new kind of propulsion system for rockets (a "space drive"), and that human explorers will use it to head for nearby star systems – worlds which, by that time, we will have already explored robotically. At that point, he said, "history will truly begin." Clarke also predicted that artificial intelligence will reach human levels by 2020, after which there will be "two intelligent species on Planet Earth," one evolving much more rapidly than the other.

Stephen Hawking seems to agree that we should be cautious in the face of accelerating computer technology. In an interview in 2001, Hawking said that human beings should change their DNA through genetic manipulation in order to keep ahead of our electronic rivals and stop intelligent machines from gaining the upper hand. "The danger is real," he said, "that this [computer] intelligence will develop and take over the world."

Inventor and futurist Ray Kurzweil agrees that a human-computer "merger" is inevitable. He predicts that by 2019, $1,000 worth of computing power will have capabilities similar to those of a human brain; by 2029, machines will claim to be conscious; and by 2099 there will no longer be "any clear distinction between humans and computers."

For a more optimistic outlook, we can turn to U.S. physicist and science popularizer Michio Kaku. In his 1997 book *Visions*, he presents a detailed look at how science and technology will transform society over the next hundred years. Thanks to advances in physics, biomedicine, and computer technology, he predicts we "are on the cusp of an epoch-making transformation, from being *passive observers of Nature to being active choreographers of Nature*" [Kaku's emphasis]. Many cancers will be curable by 2020, he says; computers will be as cheap as beer; a day trip into Earth orbit will cost about the same as a transatlantic flight. (With twelve years to go, however, some of these may be a close call.) It's a rosy picture overall, though as Kaku acknowledges, "In the background always lurks the possibility of a nuclear war, the outbreak of a deadly disease, or a collapse of the environment." Well, those *would* put a damper on things, wouldn't they?

The End of Civilization

Ah, yes – the collapse of civilization: a perennial favorite for scholarly analysis and speculation of all kinds. As we contemplate the vast stretches of time that lie ahead, it's natural to wonder if human beings will be a part of that future. Will our civilization march forward, or come crashing down? Worrying about the end of the world has been a popular pastime for nearly as long as there have been humans on our planet. Ancient cultures had no end of stories of apocalyptic destruction, and one could say that the Scientific Revolution merely put a new spin on such fears: instead of waiting for the gods to wipe us out, it raised the possibility that we would simply do the job ourselves. Scientific advances have, of course, lengthened our lives and increased our numbers; but they have also shown us, for the first time, pathways that could lead to total annihilation. Ecologist Doug Cocks has described our condition as "an escalating struggle between knowledge and catastrophe." From the Bible to the bomb to global climate change, we've always found ways to imagine our downfall.

The last few decades have brought new kinds of anxieties. In his provocative book *Our Final Hour* (2003), British physicist Martin Rees outlines some of his most urgent concerns. Until now, he says, only a nation – or at least an angry province or rebellious group – had the power to unleash havoc on a large scale. Now, thanks to advances in technology (especially biotechnology), Rees says we're entering an era in which "a few adherents of a death-seeking cult, or even a single, embittered individual, could unleash an attack."

As Rees reminds us, it's not just militant fundamentalist groups like al-Qaeda that we have to worry about; we should also fear smaller but equally deadly cults like Heaven's Gate (responsible for a mass suicide in 1997) and Aum Shinrikyo (the group behind the 1995 Sarin gas attack on the Tokyo subway), as well as angry individuals like the Oklahoma City bombers and the Unabomber. A single person, he stresses, can now become a deadly force even without a cult of like-minded followers. “There will always be disaffected loners in every country,” Rees warns, “and the ‘leverage’ that each can exert is increasing.”

Another danger, Rees says, is that society is becoming increasingly integrated and interdependent. No disaster can be truly “local” anymore: what affects one city, state, or province will automatically affect attitudes and behavior around the world. Nothing illustrates this better than the SARS outbreak of 2003: an infection that began in Asia quickly found its way to Canada’s largest city, and TV images of a few people wearing masks in Toronto instantly tainted the city’s reputation thousands of miles away. It took several years for the local tourism industry to recover.

But all of these dangers, Rees says, may be temporary – at least from a long-term perspective. Soon – perhaps before the end of this century – human civilization will spread beyond Earth. Once that happens, it is very unlikely that any one disaster, no matter how severe, will destroy our species completely. He argues that we are at a sort of bottleneck in time: today’s dangers are substantial and varied – but if we can make it through the next few decades, we may be in the clear for good.

Thinking of Copernicus at the Berlin Wall

A more abstract but equally intriguing approach to humanity’s long-term prospects comes from physicist J. Richard Gott of Princeton University (we met him briefly in Chapter 8 when we looked at cosmic strings as a proposed method of time travel). Gott uses what he calls the “Copernican Principle” to predict the longevity of our species – and, for that matter, the longevity of just about anything. The principle is named after Copernicus because the great astronomer showed us that we’re not in a “special” place – the earth is just one of many planets, and, as we later discovered, the sun is an ordinary star. Gott asserts that, similarly, we are not in a special *time*. More specifically, if you happen to come across some entity – it really doesn’t matter what the entity is – you can safely make two assumptions: you are probably not encountering it right after it came into existence, and you are probably not seeing it just before its demise. (Either of these cases would be "special" times, and therefore deemed unlikely by the principle.) It's much more likely, he argues, that you came upon the entity at some random time in the "middle period" of its existence.

Gott came up with the idea when visiting the Berlin Wall in 1969. The wall had been up for eight years, and many people wondered how long it would last. The Copernican Principle suggests that the best predictor of how long something will endure is *how long it has already lasted*. Gott's reasoning is astonishingly straightforward: he assumed that there was a 50 per cent chance that he was observing the Berlin Wall during the middle half of its existence – that is, between the 25 per cent mark and the 75 per cent mark on the timeline of the wall's history. Doing a little math, he concluded there was a 50 per cent chance that the future longevity of the wall was between one-third as long as its longevity thus far and three times that length.* Since the wall was 8 years old at that time, that meant an interval stretching from 2.7 years to 24 years into the future. As Gott emphasizes, he made no prediction of *how* the wall would come to an end, only of *when* it was likely to happen. When the Berlin Wall fell in 1989 – twenty years after Gott's visit, in accord with his prediction – he decided to write it up. His article "Implications of the Copernican Principle for Our Future Prospects" was published in the journal *Nature* in 1993.

Gott then turned his attention to the human race. He also hiked up his "confidence limits" from 50 per cent up to 95 per cent, the standard traditionally used by scientists. The technique remains the same: under the Copernican principle, there is a 95 per cent chance that you're observing some entity in the "middle 95 per cent" of its existence – that is, between the 2.5 per cent mark and the 97.5 per cent mark on the timeline of the object's history. Again doing a little math, you can have a 95 per cent confidence that the thing you're observing will last for an interval between 1/39 of its current age to 39 times its current age. *Homo sapiens* have been around for about 200,000 years, so the implication is that we will be around for at least another 5,100 years but probably not more than 7.8 million years. (Those figures, Gott suggests, are in line with the lifetimes of other hominids: *Homo erectus* lasted for about 1.6 million years, and the Neanderthals for about 100,000 years; mammal species on average seem to last for about 2 million years.)

It all sounds a bit abstract, but Gott has also used the method to predict something more down to earth (and perhaps equally difficult to forecast): the length of the runs of New York theatrical productions. In 1993, Gott predicted the closing dates for forty-four Broadway and off-Broadway plays that were running at the time, based only on their opening dates. Gott tells me that when he last checked the list, forty of the forty-four plays had closed (including *Cats*, which Gott reminds me "was supposed to be for 'now and forever'"), and none of the dates had fallen outside the limits given by the 95 per cent version of the Copernican Principle.

Not everyone has been swayed by Gott's argument. Physicist Freeman Dyson, of the Institute for Advanced Study, says one must be cautious in using "an abstract mathematical model to describe the real world." In particular, if we know that some improbable event has already happened, "then the probabilities of all related events may be drastically altered." Looking at humanity's long-term future, he then raises a point that we heard earlier from Martin Rees: that we may, in fact, live at a *very* special time – that is, humanity may be living just prior to the time when interplanetary travel becomes commonplace. Whether we take advantage of this opportunity, he explains, is beside the point. Just knowing that the "rules may change" within the next couple of centuries hampers any use of the Copernican Principle. "The knowledge of this improbable fact changes all the *a priori* probabilities," Dyson writes, "because the escape of life from a planet changes the rules of the game life has to play."

Place Your Bets

You don't need a Ph.D. to play at the Doomsday game. As the twentieth century drew to a close, Hollywood movies about Earth-destroying asteroids filled the screens, and articles on apocalyptic thinking (both religious and secular) became a fixture in highbrow magazines. (Cosmic collisions are particularly frightening because we know they have happened several times before. There's compelling evidence, for example, that an asteroid or comet smashed into the Yucatan peninsula in Mexico about 65 million years ago. The impact is thought to have triggered a drastic change in climate, killing off the dinosaurs and hundreds of other species.)

On the eve of the Millennium, the British bookmakers William Hill started taking bets on how the world will end, with odds worked out for about a dozen popular scenarios. (It's not quite clear how one would collect on such a bet.) The favorite is "war," with odds of 1,000 to 1. Climate change is a longer shot, at 250,000 to 1. Even lower down the list is an alien invasion, at 500,000 to 1. Meanwhile, the Long Now Foundation – the people behind the 10,000-year clock – have set up a website for similar long-term bets (www.longbets.org). There, users can ponder such predictions as "By 2030, commercial passengers will routinely fly in pilotless planes," or "At least one human alive in the year 2000 will still be alive in 2150." (The bets are given as "even odds," with all proceeds going to charity.) Perhaps they will set up a bet over a recent prediction by artificial intelligence expert David Levy: in his book *Love + Sex with Robots* (2007), Levy predicts that by 2050, "love with robots will be as normal as love with other humans, while the number of sexual acts and lovemaking positions commonly practised between humans will be extended, as robots teach more than is in all the world's sex manuals combined."

Predicting how human society will evolve is admittedly fraught with difficulty. Is it any easier when we look at purely physical systems? We saw in Chapter 6 how Newton's laws let us predict how an object responding to a force will move, and how well such predictions are borne out in our solar system. Laplace, as we saw, imagined that if we knew exactly what a physical system was doing – the precise motion of all its component particles – we could establish its future with certainty. When we do have a clear grip on those motions, we can indeed make such predictions: the sun will rise tomorrow; there will be a solar eclipse on August 21, 2017; and so on.

But nature thwarts our efforts on two fronts: quantum theory, as we've seen, prevents us from having perfect knowledge of the speed of any individual particle, let alone a complex system. Secondly, complex systems often evolve in a way that's incredibly sensitive to their initial conditions. (Think again of the "break" in a game of billiards: In the history of the game, have any two breaks ever been identical?) Rewind the system, change the position or speed of some object very slightly, and the sub sequent evolution will be different. Such systems are said to be "chaotically unstable." The most famous example is the proverbial butterfly that flaps its wings in the Amazon rainforest, affecting the weather in China months later. (It is quite possible that weather forecasters may *never* be able to accurately predict any particular city's weather more than about a week in advance.) A parallel claim has been made for biological evolution: Stephen Jay Gould argued that if you were to "replay the tape" of the last billion years of life on earth, it would be staggeringly unlikely to see the same creatures (including *Homo sapiens*) emerge in just the same way. Can we be any more confident when we consider the future of the earth itself?

Earth's Final Curtain

Our planet's fate is inexorably tied to that of our sun. Astronomers have understood stellar physics well enough for several decades now to predict, with fairly high confidence, the fate of our home star. It has been shining for some 5 billion years, and may shine for another 5 billion or perhaps a little more. As it uses up its nuclear fuel, however, it will undergo some peculiar contortions. Gravity will at first cause it to shrink in size – but this will make the sun's core hotter, which will actually cause its outer layers to expand significantly. At this stage, the sun will become a "red giant." After a few hundred million years (a short period in terms of the sun's lifetime), it will undergo yet another phase of heating and expansion, shedding much of the material in its outer layers, and finally collapsing into a so-called white dwarf. By this time, its mass will still be about three-quarters of its current value – but compressed into a sphere the size of the earth.

No one has investigated the long-term fate of the earth – and indeed the universe – in more detail than astronomer Fred Adams of the University of Michigan. Adams and co-author Gregory Laughlin described our deep cosmic future in their 1999 book *The Five Ages of the Universe*. When I spoke with Adams in his office in Ann Arbor, shortly before the publication of *Five Ages*, he talked me through our solar system's frightening future. The sun's initial swelling during its red giant phase, he says, will spell disaster. In 5 billion years, give or take, the earth "will no longer be a hospitable place." At that time, the sun – looming in the sky as a giant scarlet orb – will "completely fry the earth." The sun's radius will swell from its current 1.4 million kilometers up to a bloated 168 million kilo meters. Given that the radius of the earth's orbit is only 150 million kilometers, this sounds dire indeed. Due to the sun's weakening gravitational attraction, however, the earth's orbit will have expanded by then – out to about 185 million kilometers. So we will not be engulfed – yet – by the swelling sun. What is left of our planet, however, will be scorched beyond recognition, as the sun's luminosity soars to nearly 3,000 times its current level. But we will be in trouble long before then. "Before that happens – in two or three billion years' time – the sun will get hot enough that a runaway greenhouse effect will begin to make life very, very hot," Adams says. Not merely hot enough to make Al Gore downright cranky, but hot enough to boil the oceans. "So in the couple-of-billion-year time scale, the earth itself is in deep trouble as far as life is concerned." In a recent paper, Adams puts it more dryly: "Current estimates indicate that our biosphere will be essentially sterilized in about 3.5 billion years, so this future time marks the end of life on Earth."

The planet itself – now devoid of life – may linger a bit longer. Although Earth will have moved to a wider orbit, Adams explains that it will also meet with more resistance as it passes through "stellar outflow." This will ultimately cause Earth's orbit to decay, dragging the planet closer to the sun, where it will meet its doom. In that same paper, Adams describes the end of Planet Earth in two terrifyingly concise sentences: "Earth is thus evaporated, with its legacy being a small addition to the heavy element supply of the solar photosphere. This point in future history, approximately 7 billion years from now, marks the end of our planet."

Happily, this billion-year time scale is inconceivably long compared to the 200,000 years or so that our species has been around, let alone the few millennia in which we've been using technology. So perhaps we can dare to imagine that we will have spread out across the galaxy, or at least beyond our doomed solar system, before our planet's demise. Let us turn, then, to the long-term prospects for the universe itself.

The Fate of the Universe

If we lived in Newton's cosmos of absolute space and time, it would be reasonable enough to imagine an infinite future either for our species or for our remote descendants, with time ticking away without end. But the discoveries of twentieth-century physics changed that picture. After the big bang model began to solidify in mid-century, astronomy textbooks typically described two possible fates for our universe. If the average density of the universe were great enough, the universe would be "closed": gravity would eventually halt the expansion, and the universe would begin to contract, ultimately collapsing in a kind of reverse big bang known as the "big crunch." If the density were lower than this threshold, the universe would be "open": it would expand forever, and all processes in the universe would gradually "run down" in accordance with the second law of thermodynamics. The universe would become ever darker, colder, and less hospitable to life. A well-known poem by Robert Frost captures the essence of the two possibilities: "Some say the world will end in fire / Some say in ice." Until the final decades of the twentieth century, this was the best we could do: the universe would suffer one of these fates, though we could not say which one. But the universe had more surprises in store, and as the century drew to a close, it delivered a whopper.

In the late 1990s, astronomers were studying the properties of distant galaxies, very much as Hubble had done seventy years earlier (and now using, among other instruments, a space telescope named after him). This time, they focused on exploding stars, or supernovae, within those galaxies, using them to accurately measure their distances. Two international teams, working independently, carried out the surveys. One of them, the High-Z Supernova Team, was led by Brian Schmidt of Australian National University and Adam Riess of the Space Telescope

Science Institute in Baltimore. The other team, known as the Supernova Cosmology Project, was led by Saul Perlmutter of the Lawrence Berkeley Laboratory in California. Both teams compared what nearby galaxies were doing with the motion seen in more distant ones. What they found came as a complete surprise. The universe wasn't just expanding – it was accelerating.

The universe appears to have been decelerating until sometime around 7 billion years ago; after that, the universe entered a new era of ever-faster expansion. What could possibly be causing the universe to accelerate? The big bang explosion would have given everything an outward push – but the force of gravity ought to be slowing that expansion; the universe should be slowing down. Astronomers and physicists concluded that there must be some kind of energy that works against gravity – some force that literally pushes all of the galaxies away from each other. No one knows exactly what that entity is; for now it has been labeled "dark energy." It is certainly possible that this dark energy is the energy associated with empty space that Einstein had suggested back in 1917, when he introduced his "cosmological constant." If that turns out to be the case, then his "greatest blunder" was in fact a move of incredible foresight.

Even if the dark energy is Einstein's cosmological constant, however, there are still problems. Physicists are at a loss to explain exactly where it comes from, or why it has the particular strength that is has. (Their best efforts to predict dark energy's strength, based on what we know about subatomic particles and quantum theory, gives a value that's far too large, by many orders of magnitude.) The nature of dark energy remains one of the most profound mysteries in physics today.

Dark Energy, Dark Future

One thing we do know about dark energy: the extra "push" it delivers would seem to guarantee an open, ever-expanding cosmos. Today astronomers look out across the universe and see galaxies lumped together in clusters, with those clusters grouped together in "superclusters." The superclusters, in turn, appear to be strung out in vast string-like filaments that stretch for hundreds of millions of light-years across the cosmos. Gravity has crafted these structures – but dark energy will tear them apart.

As fate would have it, Adams published *The Five Ages of the Universe* just before Schmidt, Riess, and Perlmutter announced their discovery. How does the presence of dark energy affect Adams's forecast?

"Perhaps the most important update is that we now 'know' that the universe is accelerating," he told me by e-mail (using the quote marks to emphasize the fact that, in science, no result is ever 100 per cent certain). "Since the expansion of the universe is speeding up, essentially no more cosmic structure will form." In other words, those clusters and superclusters and stringy filaments are the end of the line in terms of cosmic evolution. "The things that we have now in the universe will be all that you get – ever," he says.

Thanks to dark energy, those large-scale structures will gradually disintegrate, and the universe will eventually look very different from what we see today. Things will appear fairly normal for the first few trillion years; stars will continue to shine, and any planets they may harbor could be reasonably hospitable places. Adams calls this the "stelliferous" era (the term means "filled with stars"); it is the era we now inhabit.

Eventually, however, the stars will exhaust their nuclear fuel, and – perhaps 100 trillion years from now – no new stars will be able to form. The stelliferous era will have come to an end, and we will enter what Adams calls the "degenerate era": the most prominent objects in the universe will be "degenerate stellar objects" – essentially the wasted cores of stars that no longer shine. Ordinary stars will have evolved into white dwarfs, while heavier stars will become ultra-dense neutron stars or black holes. (Very occasionally, two white dwarfs will collide, triggering a supernova explosion. In what is left of our galaxy, Adams has calculated, this will happen once every trillion years or so. Each supernova will shine brilliantly for a few weeks but in the end will decay into degenerate cores along with every other star-like object remaining in the universe.)

Ultimately, we shouldn't get too attached to these stellar remnants either, Adams cautions. After a mind-numbing period of time, white dwarfs and neutron stars will disintegrate through a process called proton decay, in which solid matter gives way to radiation. (The lifetime of a proton is not yet known, but our best theories suggest that protons last for 10^{30} to 10^{40} years.)* This marks the end of the degenerate era. After that point, the only sizable objects left in the universe will be black holes, and we enter the aptly named “black hole era.”

Black holes are the most enduring objects that our universe and the laws of physics are able to craft. And yet they, too, must succumb to the endless time of an expanding universe. Black holes will ultimately disappear, evaporating by a process known as Hawking radiation (a quantum-mechanical process first described by Stephen Hawking in 1974). A black hole with the mass of the sun may last for 10^{65} years; a super massive black hole may endure for 10^{100} years. (That number may look familiar: it’s called a googol – a one followed by one hundred zeros.)

After the last black hole has disappeared in a puff of Hawking radiation, the universe will be nearly empty. All that will remain is a sparse flotilla of fundamental particles, drifting endlessly across a frozen, featureless void. Adams calls this final epoch the “dark era.”*

If we could somehow transport ourselves to this distant era, what would we see? “Very little,” says Adams. “The universe would be very, very dark, very diffuse.” All that will remain is a “very diffuse ‘soup’ of particles. Mostly elementary particles: electrons, positrons, neutrinos, and photons – and perhaps other things that we don’t know about.” Not much can happen in this rarefied environment, Adams explains. Occasionally, an electron will bind with a positron to form an atom of “positronium” – but even these will eventually disintegrate. Electrons and positrons can also directly annihilate with each other. “And except for these low-level annihilation events,” says Adams, “the universe is a very low-energy, low-key kind of place … A sea of darkness.”

It is perhaps T.S. Eliot rather than Robert Frost who came closest to the mark: “This is the way the world ends / Not with a bang but a whimper.”

The End of Astronomy

It is hard to think of anything more depressing than this slow decline of the cosmos into eternal darkness. But here goes: because of dark energy's unforgiving push, the night sky of the remote future will be far less rich than the one we see today, and astronomers of that era will have no inkling of the vast and complex cosmos that once existed.

The Milky Way and its closest neighbor, the Andromeda Galaxy, are bound together by gravity; together with a sprinkling of "dwarf" galaxies, they make up the so-called Local Group. The billions of other galaxies beyond the Local Group are not gravitationally bound to us, and the expansion of the universe, driven by dark energy, will eventually push them out of view. The most distant objects will be the first to disappear – "cloaked behind a cosmological horizon," as Adams puts it. Nearer galaxies will follow, slipping away one by one.

By 100 billion years from now, give or take, even the Virgo cluster – the next-closest cluster of galaxies beyond the Local Group – will have disappeared over this cosmic horizon. We will be completely isolated from the rest of the universe: beyond the handful of galaxies that make up our Local Group, our telescopes will reveal only blackness. All of those other clusters will suffer the same fate; each of them will be similarly isolated from *its* neighbors. Should astronomers exist in those other realms, their telescopes, too, will reveal nothing. Kant's vision of "island universes" will have been realized in the most literal way.*

Our Local Group will still see some action: our galaxy and the Andromeda Galaxy are currently moving toward one another, and they are expected to merge in about 6 billion years. (The merger will not directly affect most stars: because stars are very far apart compared to their individual diameters, a typical star will not itself undergo a collision.) In the long run, the Milky Way, Andromeda, and the other smaller galaxies of the Local Group will merge into one large conglomeration.

When our Local Group becomes a universe unto itself, astronomers will have things to aim their telescopes at "locally" but will be ignorant of the universe's overall structure. As Lawrence Krauss and his colleagues have recently argued, astronomers of this distant era will be hard pressed to infer that anything like a big bang had ever occurred: with those distant galaxies red-shifted into oblivion, it will no longer be possible to make the discovery that Hubble made in the 1920s. The cosmic microwave background radiation, meanwhile, will suffer a similar fate: as the CMB radiation gets stretched out to longer wavelengths, its signal will be lost among radiation from other sources. Krauss says that astronomers living at that time will be misled: "It will lead them to the wrong conclusion about what the universe is doing. The universe will look static, and that's vastly wrong, because the universe is expanding so fast they can't see it."

This is troubling on many levels. It is naturally disheartening to think of knowledge that we have today no longer being available in the remote future; perhaps it will make us strive to preserve that knowledge at all costs. It may also make us wonder just how confident we should be in our interpretations of what *we* see in the sky right now. On the other hand, there has got to be a compelling science-fiction tale in all of this: *Civilization A proudly declares that they have mapped the entire universe, only to be confronted by Civilization B, whose dusty records of long ago describe a night sky that told of a more wonderful and infinitely larger cosmos, now lost …*

The End of Life

We have seen how the universe is destined to end in darkness; what, then, is the fate of life in the universe? The second law of thermodynamics, once again, seems to dictate our destiny. In an open universe, it would seem that every entity, every being, every thought, must come to an end. As the philosopher Bertrand Russell once put it, "All the labours of the ages, all the devotion, all the inspiration, all the noonday brightness of human genius, are destined to extinction … The whole temple of Man's achievement must inevitably be buried beneath the debris of a universe in ruins."

In the late 1970s, however, Freeman Dyson suggested a way out: he imagined "life" in more general terms as anything that can process information. Because information processing requires energy and generates heat, it would seem as though an expanding universe offers less and less usable energy to keep such a system functioning. Dyson suggested that life could in effect "hibernate" for ever-increasing periods of time. By lengthening the span of the hibernation periods – effectively lowering their "metabolism," so to speak – life could endure more or less forever, he asserted.

With the discovery of dark energy, however, Dyson's strategy may no longer work. Physicists Lawrence Krauss and Glenn Starkman considered the problem in the late 1990s and found that life is indeed in trouble. Life requires energy, they reasoned, and in an accelerating universe, it becomes more and more difficult to collect and harness that energy. As we become isolated in our respective "island universes," the resources at our disposal become strictly limited. With finite resources, any living creatures (or equivalent machines) would have a finite memory, they argue, and "would eventually have to forget an old thought in order to have a new one." Finite information, they argue, implies a finite number of thoughts. In the end, thinking entities would be left with little to do but to have the same thoughts over and over again. "Eternity would become a prison, rather than an endlessly receding horizon of creativity and exploration." In the long run, "life, certainly in its physical incarnation, must come to an end."

This is not a particularly happy outlook for life, the universe, and everything, but perhaps we can take away something positive from our speculation. First of all – and I seem to recall Carl Sagan saying something like this toward the end of his TV series *Cosmos* – all those billions of years that lie ahead offer the opportunity to do a great deal of good. Further, it is quite impressive that with our finite hominid brains we have been able to peer so far ahead, with at least some degree of confidence. It is also rather intriguing that the fate of the universe billions upon billions of years in the future is actually clearer to us than the fate of our own civilization just a few centuries from now.

Perhaps our descendants will congregate in the Nevada desert and stand in awe before the Clock of the Long Now, in the same way that tourists today stand humbled before the pyramids of Egypt. Or not. It is anybody's guess if the fruits of this ambitious project will endure for so many generations. Physicist and writer Gregory Benford, for one, suspects the grand ten-thousand-year clock may meet its demise on a much shorter time scale. The prototype clock is "too pretty," he says. He hopes that the full-sized version planned for the desert is less shiny. "The first biker gang to come along is going to trash this thing," he says. "If they had made it rugged and ugly, it might last."* Writer Brian Hayes is even more critical: by assuming that civilization ten thousand years from now would share any of our values, let alone our desire to keep track of time, we're committing an act "of chronocolonialism, enslaving future generations to maintain our legacy systems." Hayes acknowledges that it is noble to act in the best interests of posterity – but wonders how we might guess what those interests would be, beyond a few generations. "To assume that the values of our own age embody eternal verities and virtues is foolish and arrogant," he writes. "For all I know, some future generation will thank us for burning up all that noxious petroleum and curse us for exterminating the smallpox virus." Even the five-digit coding of the years, which seems like a good way to avoid a "Y10K" crisis on New Year's Eve, A.D. 9999, is wrong-headed, Hayes argues. Four digits, he says, is plenty. "If we take up the habit of building machines meant to last past 10000, or if we write our computer programs with room for five-digit years, we are not doing the future a favour. We're merely nourishing our own delusions."

Indeed, Hayes notes that in centuries past, other clocks were built with lofty hopes that they would run for equally lengthy periods. He cites the example of the grand astronomical clock in Strasbourg Cathedral, originally crafted in the 1300s. Two centuries later, when a team was brought in to repair the clockwork, they instead chose to start from scratch. The clock was overhauled again in the 1700s, and once again workers installed a new mechanism instead of repairing the previous machine. Hayes suspects that the Clock of the Long Now, ambitious as it is, will be similarly overhauled and replaced long before its ten thousand years are up. At the very least, the full-scale version will have to be different from the London prototype in one very important respect. I said earlier that the prototype "ticks twice a day," and that its three-pronged pendulum "rotates back and forth" – but I should really have said that the clock *would* tick, and the pendulum *would* swing, if the clock were actually running.

Apparently the clock was switched off when it was shipped from California to England, and since being installed in the Museum of Science it has yet to be switched back on. It was inert at the time of my visit, and remained so as of early 2008. Part of the problem, a spokesman for the Long Now Foundation says, is the glass case that now surrounds the clock, making it difficult to wind the mechanism. The goal is to come up with a motorized winding/driving mechanism that can be maintained without opening the case, he says. It's not quite clear how long this upgrade will take.

Until then, the clock designed to speak across the ages remains silent.

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* We looked at precession briefly in Chapter 1.

* At least for those who consider the millennium to have begun at the start of 2000 rather than 2001.

* Suppose the entity has been around for x years. If you are seeing it at the 25 per cent mark on the timeline of its existence, then its future duration (beginning now) is three times greater than its past duration, i.e., $3x$. If you're already at the 75 per cent mark, however, then its future is only *one-third* as long as its past, i.e., –1/3 x. So your 50 per cent confidence zone (75 per cent − 25 per cent = 50 per cent) stretches from a future –1/3 x in length to a future $3x$ in length. (A parallel argument can be used for the 95 per cent confidence version of the argument.)

* These are very large numbers indeed. Remember that the age of the universe at the moment is only about 10^{10} years.

* I have mentioned four of the "five ages" that provide Adams with the title for his book. Our current age, the stelliferous era, is the second; it was preceded by the "primordial era," which covered roughly the first million years of cosmic history, from the big bang to the creation of the first stars.

* One way to think of this disappearing act is that these galaxies will be receding from each other faster than light can travel the distances that separate them. (This sounds like a violation of special relativity, but it isn't: it is the expansion of space itself that is driving the galaxies apart.) Equivalently, we can think of their light as being so severely red-shifted as to be undetectable.

* In his book *Deep Time* (1999), Benford gives another startling example of our failure to

communicate across time: many “time capsules” that have been sealed (and often buried) by well-meaning citizens, for the interest of future generations, have since been lost, either by “markers” not being erected or by the locations of the capsules simply being forgotten. He notes that the city of Corona, California, has laid down seventeen time capsules in the last fifty years – and has lost track of all of them.