# Deep Time

## The Jouney of a Particle from the Moment of Creation to the Death of the Universe and Beyond

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# Chapter 1: Prelude

*Whence come I and whither go I? That is the great unfathomable question.*
– Max Planck

Without time, without space. Without matter or energy. This is the beginning of the universe, and there is nothing – not even a point, not even a void.

Out of this nothingness there arises a stir – an eddy, a flicker, a something inconceivably small. And with that something, as part of it, time, space, and other wonders come spontaneously into being. The lid of Pandora's cosmic box has begun to lift and from beneath it issue all the marvels of creation.

Yet by whose hand has that lid been set ajar? And if the answer is "No one's," then how is the magic of genesis performed?

* * *

Countless myths are told of the creation. Myths both ancient and modern, steeped in wonder, each offering its own special window upon the genesis event. From India and China, from the native cultures of Africa and Australia and North America they come. Summoning all manner of gods and heroic creatures to do the seemingly impossible, to bring the world into being. And not just the world but the sun and moon and stars as well, and, in company with these, all of space and time.

And now these older tales are joined by fresh myths born not of faith, not of archaic wisdom unchallenged, but of science, yet no less strange for all that. Gone may be the gods – gone, at least, is their essential presence at each stage in the shaping of what is real. Now nature alone is seen as potent enough, creative enough, to draw itself into existence.

In the beginning, so these new myths of science would tell us, there was nothing. Absolutely nothing. Not matter, or energy, or space, or time. Then came a tiny hiccup, a trivial fluctuation that transformed nothingness into something. Perhaps, our myth would have us believe, the primordial nothingness was unstable.

Remarkable. The universe born out of nothing, of its own accord.

But no – not entirely nothing. For if time itself had its origin with some capricious inaugural event, then how did that event manage to occur at all? How could the act of creation begin outside of time?

Unless the rule book of nature was written prior to genesis, how could a state of unbeing know that it had to change? Is nothingness not a much simpler condition, therefore one more likely to prevail, than that of a universe teeming with exotic forms of matter and energy? To all appearances the absence of anything could hardly be more perfect. Why should it sully itself with the seed of stars and stargazers?

This is the central dilemma of genesis – and it afflicts all cosmologies, ancient and new. Wherever the universe came from, before it could emerge there had to be guiding principles, preexisting natural laws. But where did those laws come from? And, in any case, how can a law exist disembodied and outside of time?

Perhaps "before" the laws of physics came the laws of logic, so that the physical laws chosen were the only ones, in combination, that proved logically consistent. But who said the cosmos had to be logical? And whence did the rules of logic appear?

* * *

Time is a marvelous trickster. But one of the greatest hoaxes it perpetrates is to make the creation of the universe seem like the beginning of everything.

Imagine a stream that courses down a tall mountain. At the foot of the mountain, on the banks of the stream, there dwells a tribe. To the people of this isolated commune the stream, with its clear, refreshing water, is all-essential. It is their very lifeblood. And so, because of this, it is also the focal point for the musings of the tribal wise. Where does the stream come from? What is its true beginning? So steep and high is the mountain that none can scale it to seek a definitive answer. And so the wise contrive their theories and spend their days arguing this way and that. It is the god of the mountain, say some, whose tears, shed for the loss of his beloved son, tumble down as the waters of the stream. No, insist others, that is only an admission of ignorance. The stream must somehow issue naturally out of a crack near the mountain's summit. But what happens within the crack – there remains a mystery.

Each day the tribe is blessed with cloudless skies. But almost every night, when the people sleep (and they sleep very soundly), it pours with rain. The rain falls on the mountaintop, collects as a stream, and serves, with each new day, to sustain the tribe and its puzzled priests. Farther down the valley, where these insular folk never venture, the little stream grows to become a river. And, after hundreds of miles, the river reaches the sea, whose water then evaporates to form clouds, which in turn drop rain on the great mountains, to feed the stream that nourishes the tribe. How short-sighted of these primitive folk never to have realized all this!

But then, what of the universe? To the high priests of science, and philosophy, and theology, that, too, is usually regarded as having some special point of origin. And yet is this not just as myopic a view as that held by the sages of our imaginary tribe? The stream, it transpired, had no true source, no real beginning. Might the same not be true of the cosmos?

* * *

There is only one solution to that greatest of all mysteries, the origin of everything. But to understand it requires that we go on a mental journey, perhaps the most daring ever undertaken. It is a voyage into Deep Time, a voyage that begins with genesis and ends in the very remote future of a universe that, quite astonishingly, contrives to become aware of itself.

# Chapter 2: Symphony

*And God said, Let there be light; and there was light.*
– The Book of Genesis

There are no landmarks here. No galaxies, no stars. No elaborations of matter of any kind. Only one second ago the universe itself began in the most titanic of explosions, an explosion in which all the matter and energy there would ever be spontaneously appeared and was borne swiftly out upon the stretching fabric of space. One second old is the universe, and it is filled exclusively with the steaming, fertile brew of creation.

Out of that brew, in due course, will emerge minds fashioned exuberantly of stardust. Presently, these will awaken to their astonishing origins. They will begin to appreciate that they are, quite literally, star children. That they are the universe peering in upon itself. Some of them will even organize patterns of symbols that they might better share such self-reflexive thoughts with their fellow stardust minds. All this is inevitable. So, too, the emergence of sea gulls and spaceships, solar flares and Chevrolets.

But for now there is no such complexity. There is only the raw, untamed potential for it. Potential that, within the one-second-old cosmos, takes the form of a host of loose subatomic particles darting about, colliding, and interacting. And doing so, moreover, not aimlessly, but, rather, in mysterious, blind allegiance to some grand natural code.

Each of these particles eventually will have its own fabulous tale to tell. Of its exploits in the misty netherlands close to genesis. And of its adventures, too, in the greater universe to come, in that vast ocean of time stretching away from creation's shores to those of the most distant future.

Here, now, is one such story, part truth, part fable. A natural history of the universe as glimpsed through the eyes of a single, mythical subatomic particle.

* * *

That particle, the paladin of this tale, chances to be a proton. And as such, as luck would have it, it ranks among the heartier pieces of matter in the infant cosmos. Barely a trillion of its kind would it take, arrayed side by side, to span the dot over this "i"; a mere thousand times that number would suffice to tip the scales against a modest-sized virus.

So comparatively huge is our proton that it seems almost planetlike amid the early universe, a smooth, white, Venus-in-miniature careering through space, with other such particle worlds dimly visible in the distance. Of these some are protons, indistinguishable from our own; the rest, neutrons – similar in size, hued in battleship gray.

Still far off is the age when protons and neutrons will be able to forge a lasting alliance, to come together in tight, permanent clusters. Yet when that does happen these two particle types will emerge as crucial building blocks. They will emerge as building blocks for the nuclei of stable atoms, and so, as the substrata for more mature forms of matter, even for consciousness itself.

Nothing else seems to occupy the newborn universe. Nothing, that is, save for a dazzling, all-pervasive glow. And yet that glow conceals an inner quality. There is a fine texture to it, a shifting, sparkling texture. Indeed, far from being continuous and bland, this iridescent seas swarms with a myriad of lowlier particles, a billion of them for every proton and neutron.

Suddenly, without warning, one of these lesser specks of matter streaks directly across the path of our advancing proton, scarcely avoiding an impact. Like a coal-black meteor it seemed in comparison with the proton's bulk. But there could be no doubting its true identity. This was an electron, a member of the third species of particle that, together with protons and neutrons, are needed for the fabrication of atoms. Its negative electric charge exactly balances the positive charge of the proton. In mass, however, the electron is a dwarf, over 1,800 times lighter than either the proton or neutron. And in size – even a meteor is too lofty a description. For the extraordinary fact is, the electron seems to have no size at all, to be simply a dimensionless point.

In all directions the electrons abound, over 100 million of them to our single proton. And yet they are not the only species of swarming horde. There is also the positron. And here is a very strange thing. For the positron seems to be the complete antithesis of the electron, a sort of mirror image – white meteor to the electron's black.

Nor is the electron unique in having a counter-self. To every fundamental particle in nature there is a corresponding "antiparticle." An antiproton, an antineutron. And so on. Always, particles and their antiparticles are equal in mass. But other of their properties, such as electric charge, are reversed. So, for instance, the positron bears a charge that is as much positive as the electron's is negative.

Most surprising of all is what happens when particle and antiparticle meet. For then they completely annihilate one another, freeing the energy previously pent up inside them as a pair of entirely new particles – particles known as photons.

Everywhere now the crackling of electrons annihilating with positrons becomes apparent, like the noise of some overworked Geiger counter. And yet that mutual act of destruction also prompts a question. For why do so many electrons and positrons remain? It seems that, despite their efforts to extinguish one another, their numbers remain more or less the same.

Re-enter those mysterious photons, products of the electron-positron clash. These make up a third superpopulous particle tribe, as numerous even as the electrons and positrons. But, at the same time, they are a very different breed. For photons, it turns out, rather unexpectedly, are particles of light.

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Rainbows. A star in Orion. The Mona Lisa's smile. Light may be all of these – or at least the bearer of information about them. And yet – a stream of tiny particles? So, at the subatomic level, may it behave.

A light particle, a photon, is not a material thing. Its substance is not of matter but of pure energy. And the fact that it vaunts energy alone enables it to do what no material particle in nature can – to travel at the ultimate cosmic speed (186,282 miles per second in empty space), but it can travel neither slower nor faster than that. To impede a photon, to trap and examine it, is to destroy it and so free its energy for some new purpose.

Most unusual is what may happen when two photons collide. If, together, the photons have enough energy, they may give rise to a fresh pair of particles, one particle plus its antiparticle. What is more, the offspring of this "pair-creation" process may be particles with mass. Mass from energy. Strange. Strange, at least, it seems to dwellers of a macroscopic world. That matter and energy should be two sides of the same coin. That matter is mere patterned energy; energy, the formless clay out of which material things arise.

Now the reason the annihilating electrons and positrons remain so numerous becomes clear. Directly above our proton, two photons – glittering Fourth of July rockets – converge, collide. And abruptly vanish. In their stead materializes an electron-positron pair! And it is the same throughout the rest of this young cosmos. The rejuvenation of the warring electron and positron hosts is everywhere taking place. As fast as the antagonists are slaying one another, new recruits are being introduced to the fray through the efforts of the photons. Which is to say, the electrons and positrons and photons are in dynamic equilibrium so that the number of each, one second after genesis, is maintained approximately the same.

But what of the protons and neutrons? Why are they not being created, along with their antiparticles, from photon collision?

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Like all newborns, the cosmos is small. Not nearly so small now, perhaps, as it was but a heartbeat ago. Yet very tiny still compared with what it will become.

Imagine all the substance of 100 billion galaxies drawn into a bubble of space only 200,000 miles across – less than the distance from the Earth to the Moon. Such is the condition of the one-second-old universe.

Take a bicycle pump. Pump it several times, and the air inside becomes warm. Compression causes heat.

Take the universe. Squeeze its entire contents into a ball 200,000 miles across. And the cosmic matter becomes hot. Searingly hot. One second after genesis the universe swelters at ten billion degrees centigrade. By comparison, ground zero of a nuclear blast would seem the very essence of tranquility.

Ten billion degrees: At that temperature the energy of a typical photon is more than enough to provide the stationary mass of an electron or positron. Thus from two colliding photons may come an electron-positron pair.

But recall: The electron is an extremely light particle. A proton or neutron is over 1,800 times heavier. So a proton-antiproton pair, for instance, could come only from the union of two photons with at least 1,800 times the threshold energy needed to make an electron and positron. Not even a cosmic oven running at ten billion degrees can cook up such super energetic particles of light. But earlier in the history of the universe? Then might the temperature have been higher still, high enough perhaps for much more massive particles to spring forth from the photons' pas de deux.

As it is our proton moves more securely now. No antiprotons stalk in the particle undergrowth around, threatening it with instant oblivion. All of the antiprotons have gone. So, too, the antineutrons. Presumably, they became extinct through pair annihilation with ordinary protons and neutrons in some earlier age. And that raises an enormous question. For if all the antiprotons and antineutrons have disappeared, then why not all of the protons and neutrons as well? For some reason there must have been an excess of the latter. And that excess is crucial. Because in time it will form the basis for the development of more ornate patterns of matter – like the author and the reader.

With dark mysteries such as these does genesis beckon. So compellingly that to ignore its siren call now and press on into the future – that would be to forgo much, perhaps the very secret of existence itself. The cosmic clock must be thrown into reverse.

And so it is done. Back our proton begins to slide, back down the path along which it came, to descend once more through those micro strata of time that separate it from the origin of everything.

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Presently that close encounter with the electron-meteor, already described, takes place again, but now in reverse. The electron flashes by, this time in the wake of our retreating proton.

Another electron spears past, perilously near. Followed by another, and another. And then the inevitable: Squarely on, our proton is struck by one of these speeding mavericks. For an instant it seems as if the luckless electron may simply be engulfed, as a fist-sized meteor would be by the Earth, without effect. But then, rapidly, from where the smaller particle buried itself into the larger one's surface, a gray shadow begins to spread outward. Soon that grayness has enveloped the whole of our proton. And our proton is no more. It has been transformed – into a neutron! (In forward time, of course, this would be seen as a neutron decaying into a proton plus an electron.)

Here, then, is another kind of particle reaction common with the early universe. Already, photons in collision have been seen to give rise to electron-positron pairs; electrons and positrons in annihilation to yield photons. Now, it transpires, an electron may merge with a proton to spawn a neutron.

But not simply a neutron. When the electron struck, a second particle, a wraithlike thing, sprang from the midst of the reaction, only to hasten away at vast speed. It was a neutrino, one of nature's exiles, bizarre and aloof.

Billions of neutrinos from the depths of space have passed unmolested through the reader's brain in the time it has taken to assimilate this wild thought. Some came directly from the one-second-old universe itself. Most, by now, have also navigated clear through the body of the Earth as if it were a vacuous ball. Neutrinos move at, or very close to, the speed of light. They are either massless or the possessors of a mass so small that it has not hitherto been measured. And hardly ever do they court the attentions of ordinary matter. A light-year of lead would pose little threat of absorption to one.

But in the subsecond cosmos the state of matter is far from ordinary. The particle soup here is very, very thick indeed. So thick, in fact, that even a spectral neutrino may not move through it far without the risk of interaction.

Just as an electron and a proton may combine to produce a neutron and a neutrino, so, under the extreme conditions of the early universe, the reverse reaction can as easily take place. Within the first second of creation, neutrons and neutrinos find it a simple matter to unite and produce protons and electrons. In complementary style a neutron and a positron may collide to yield a proton and an antineutrino. And to complete the round: From colliding protons and antineutrinos may come neutrons and positrons.

All of which suggests, at first, unbridled confusion. In this primal subatomic riot, incited by ultrahigh densities and temperatures, the various particle species seem capable of interacting at will, randomly, in any fashion. Protons, neutrons, electrons, positrons, photons, neutrinos, and antineutrinos– the main particle types in the cosmos at this stage – all are implicated. And the result: apparent chaos, apparent anarchy.

And yet, in truth, there is an underlying order, well concealed perhaps, to what goes on here. The particles cannot combine ad libitum. Nor are the results of their collision altogether arbitrary.

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The universe is like a game of chess. It has rules. And those rules govern the actions and behavior of everything there is, including subatomic particles, just as the rules of chess dictate how chessmen may move.

For example, there are conservation rules. Certain quantities, nature demands, must pass through a particle reaction unaltered. Among these – energy. The summed energy (including energy in the guise of mass) of the particles entering a reaction must exactly balance that of the particle products. Energy, overall, can neither be created, nor destroyed. Only can it be reforged, recast.

And, in like manner, nature insists always that electric charge be conserved. What charge goes in must also come out. As when our proton mutated into a neutron. Proton and electron (total charge: +1 + (-1) = 0) gave rise to neutron and neutrino (total charge: 0 + 0 = 0). Had our proton, on the other hand, met with a positron, it could not have produced, say, a neutron and an electron. For then, in flagrant violation of charge conservation, the total charge would have had to change from +2 to -1.

Thus nature sets strict limits on the possible variety of ways that basic particles can mix and match. And yet not only through the conservation of energy and charge does it do this. There are other quantities, too, that it decrees be left unaltered, quantities wholly unfamiliar at the macroscopic level, and so apparently arbitrary that they suggest a much deeper significance to nature's rules. They suggest that not only do these rules control how matter and energy behave but that they also determine exactly the basic forms that matter and energy can take.

Which returns us to our chess analogy. For is this really not also the case with chess? That the rules of the game govern not simply the movements of some pre-existing chess pieces but that those rules, in some sense, actually create the pieces. Forget, for a moment, the superficial appearance of a bishop or a rook or a pawn. The way it is carved, whether of ivory or wood, even its physical presence on a physical board – these are not what fundamentally matter (chess, after all, can be played in the head). It is the definition of what a piece can do, how it may move, how it may interact with other pieces, that is its true and central essence. And that definition follows directly from the game's precepts.

So it is with the universe. The laws of nature lay down precisely, uniquely, the fundamental modes in which matter and energy occur. They define, in other words, the scope and properties of subatomic particles. Moreover, they bring into being the intangible essence, the potentiality, of those particles. And yet here is a critical point: Why those specifically?

Just as in chess there is a small repertoire of pieces – a rook, a queen, a knight, and so on – so in nature there is only a limited number of different particles. There is an electron, a proton, a neutrino. But, for example, there is no particle with ten times the mass of the electron and twice its charge. Nowhere does nature's design provide for such a creature, just as surely as chess makes no allowance for a piece that may leap over three others in a single move.

The cosmic rule book defines just certain types of particle. But not only that. It defines them in such a way that they seem to fall quite neatly into family groups. One such family, the baryons, or "heavyweight" particles, includes the proton, the neutron, and their antiparticles. A second clan, the leptons, or "lightweight" particles, includes the electrons, the neutrinos, and their antiparticles.

Now those additional conservation rules, alluded to earlier, make their appearance. For the universe, it turns out, is meticulous about keeping the separate populations of leptons and baryons at a constant level. Always, in any particle reaction, the total number of baryons less antibaryons and the total number of leptons less antileptons remains the same. And that is extraordinary, for these quantities – the so-called baryon number and lepton number – play absolutely no other part in the physics of the cosmos. Whereas charge and energy, for instance, as well as being conserved quantities, exert obvious dynamic effects, the baryon and lepton numbers seem merely to be a cosmic accounting device.

Why should the universe be this way, why so incredibly contrived? Why should it follow one particular set of rules – one seemingly so arbitrary rather than any other? Who or what made this special selection?

We are like the priests of that fictitious tribe, puzzling over the origin of their mountain stream. Yet we are also bolder than they. For now we are heading up the mountain, swimming back against time's current, moving ever closer (so we guess) to the ultimate source of the cosmic stream on the topmost peak.

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Our proton has reached to within just one tenth of a second of Time Zero. And now space seems more confined, more congested than ever. The temperature has soared to a tropical 30 billion degrees; the density has risen to over 10 billion trillion trillion times that of lead.

And yet, spectacular though these changes may be, they are quantitative only. True, the particle soup has grown hotter, thicker, even than before. But in content or structure it has not much altered. And that is perhaps surprising, even disappointing. For now the time for such significant change appears fast to be running out. Only one tenth of a second remains before the supposed wellspring of creation itself comes into view. And what is that mere finger-snap of time compared with the billions of years available for cosmic evolution to come? Is genesis about to be exposed as a non-event, as the greatest anti-climax of them all?

Not quite. Time, that master magician, is up to its tricks again. For now it would have us believe that it is a simple thing, a linear thing, always to be considered in equal intervals, each of the same importance (an illusion our clocks serve to strengthen). And yet, of course, that is nonsense. What matters, what is crucial, is not the size of a time interval but what happens within it. During the first one tenth of a second more took place, very much more, than in any similar-length period that followed. The universe underwent more transformation, experienced a greater richness of events, in that first split second that in all the billions of years of star-making and galaxy-building to come.

But how to grasp such a concept? How to become aware of the immense potential for change within even the most slender time slices close to genesis?

First, we must abandon the usual linear way of depicting time. In its place set up an exponential scale in which successive, equally-spaced divisions signify not some fixed increment of time but rather a tenfold leap in its value from the previous division. Bring in, too, a new style of notation. So that, for example, the time of one second after the start of the universe is shown as 100 s, on the exponential scale. Immediately before this comes the division marked $10^{-1}$ s, or one tenth of a second; immediately after, the division labeled $10^{1}$ s, or ten seconds. So organized, the axis of time accords the same priority to the period between one tenth of a second and one second as it does to that between one second and ten seconds.

Continuing the exponential scale into the past, further milestones are placed at $10^{-2}$ s (one hundredth of a second), $10^{-3}$ s (one thousandth of a second), and $10^{-4}$ (one ten-thousandth of a second). And now the wealth of opportunity for cosmic development within the first few moments of creation starts to become clear. For on this new scale the "gap" between one ten-thousandth of a second and one thousandth of a second is as broad as that, say, between $10^3$ (a thousand) seconds and $10^4$ (ten thousand) seconds. The possibility, at least, emerges that what previously may have been dismissed as trifling instants of time near to genesis could, in fact, rival in importance much longer intervals (as measured linearly) that occurred later on. Taken to an extreme, the potential for significant change within the universe may have been as great, for instance, between $10^{-36}$ and $10^{-35}$ of a second (a gap of only nine trillion trillion trillionths of a second) as it was between $10^{18}$ and $10^{19}$ seconds – a span of over three billion years!

Of course just placing the whole cosmic timescape within a fresh frame in no way alters time's basic nature. That is not the point of the new scale. The point is to highlight an aspect of time that already exists but is easy to overlook. Namely, that time can accommodate a vast number, an unlimited number, of events of critical significance even within its smallest recesses. That, in fact, the universe can evolve out of all recognition within one of time's most fleeting moments – especially when that moment happens to be among the very first.

Think of a human analogy. Think of someone who, as an adult, may take months or years to master an important new skill. Who would guess that within a similar time space, as a young child, that individual had discovered how to breathe, eat, accurately recognize faces and objects, crawl, walk, draw, even talk – skills of astonishing complexity and subtlety.

The universe, too, as a child, learned at a remarkable rate. It learned faster when young because, like a human child, it was much smaller, and all of its internal processes ran correspondingly swifter. The closer the time to the moment of its birth, the more frenetic was its activity and its rate of development. Brief though one tenth of a second may seem in later context, to the juvenescent cosmos it must have appeared as endless, as eventful, as any hot summer in childhood.

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So now, imagine: Ahead, in the midst of the early subatomic melee, our particle. Below, extending in a thin luminous band across the base of our field of view, a scale like that of a clear tape measure. Time values, marked exponentially on the scale, drift slowly, steadily, past a fixed pointer that reveals the current time reading. Its value now: $10^{-2}$ s AG, one hundredth of a second After Genesis.

And increasingly our particle hero seems to be suffering from an identity crisis. Under heavier and heavier bombardment by electrons, positrons, neutrinos, and antineutrinos, it flits ever more rapidly back and forth between neutron and proton states, from gray to white and back again. So much so that the generic label "nucleon," embracing both proton and neutron, from this point on will serve it more aptly.

All around, the dawn particle sea roisters. Amid seething waters of 100 billion degrees our nucleon now moves, buffeted and tossed by the currents of a fluid inconceivably more dense than any ocean on Earth.

Yet still the blend of particles is more or less the same as before. Liberal amounts of the finer ingredients, electrons, positrons, photons, neutrinos, and antineutrinos, remain delicately, but essentially, spiced with the much coarser nucleons.

Onward our particle flies. Beyond $10^{-2}$ s AG, beyond $10^{-3}$ s, ever on, in a madcap dash to keep its appointment with genesis.

Now the cosmic chronometer reads just $10^{-4}$ s AG, one ten-thousandth of a second after the start of it all. And at last, it seems, the promise of change hangs heavy in the air. Out of a nearby collision of two photons, a proton-antiproton pair appears. A moment later, in the middle distance, a neutron and antineutron emerge in similar style. More and more the process is repeated, as the universe surges past the critical temperature, about ten trillion degrees, at which nucleons and antinucleons form.

But remember: Throughout all this the cosmic clock is running backward. So that, in fact, what is happening now is the final destruction of the antiprotons and antineutrons seen in time-reverse order.

Further our particle moves into the past. Further the universal temperature climbs, well beyond that of the nucleon threshold, so that greater and greater are the numbers of protons, neutrons, and their antiparticles being spawned in the space around.

By $10^{-6}$ s AG the nucleon-antinucleon population has risen outrageously, 100 millionfold. Risen to be as high as that of the leptons and photons, for by this time all of these particles are being created and destroyed continuously, and with equal ease, during subatomic collisions.

Now that riddle of the antinucleons' disappearance, hinted at earlier, stands firmly astride our path, demanding our attention. For these are the stark simple facts:

At $10^{-6}$ s AG the numbers of nucleons, antinucleons, and photons are, to all appearances, equal. Yet by $10^{-4}$ s AG only one nucleon survives for every 100 million photons, and there are no antinucleons left at all. Since the sole way nucleons and antinucleons can be destroyed is by annihilating with each other on a one-to-one basis, we are left with a remarkable, almost unbelievable, conclusion. Namely, the original populations of nucleons and antinucleons were not exactly the same. There is an excess, in the one-microsecond-old universe, of roughly one nucleon for every 100 million nucleon-antinucleon pairs. And tiny though that excess may seem, it is both intriguing and momentous. Intriguing because it proves beyond all doubt that the rules of nature have a peculiar built-in bias for matter over antimatter. And momentous, as already suggested, because that relatively small band of nucleonic survivors will become the basis for all the important structures in the universe to come.

Why should the cosmos not be completely even-handed in its treatment of matter and antimatter? The origin of asymmetry, any sort of asymmetry, seems as incredible as that of the universe itself. Who told nature it had to be lopsided?

But even as the question is asked, our attention is diverted. For now, just as the time gauge slips past $10^{-6}$ s AG, another tremendous change takes place. Our particle world, our seemingly secure rock in this unsafe cosmos, abruptly breaks up! In a flash its large gray-white spheroid form is gone, shattered. But shattered not into various odd, sizable chunks, like a real planet that had disintegrated, but into three of the tiniest specks imaginable. No bigger than the pointilistic electrons are these. And their name – quarks.

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Faster than we can follow, two of the quarks born of our nucleon's demise escape, losing themselves in the particle maze around. Only one remains on center stage to become our new hero, or rather our old hero in its new and lessened form.

And the other nucleons in space? They, too, it seems, are bursting spectacularly apart, showering space with their component quarks and antiquarks. Neutrons and protons were not, after all, truly fundamental particles. Each was a bound state of three much smaller flecks of matter, a bag of quark triplets.

But how did the quarks come to be in such bags? The answer to that has to do with the nature of quarks and, in particular, with the nature of the force that operates between them, which is very odd indeed. Quarks attract one another with a force that actually becomes stronger the farther the quarks are apart, as if each were joined to its neighbors by means of an unbreakable elastic thread. Closely packed, quarks behave as if they were free – almost as if they were content that others of their kind were nearby. Yet if any attempt is made to separate them, the quarks immediately counter this by pulling each other more and more powerfully together. So intense is their social urge that quarks simply cannot be made to exist in isolation.

Now, apparently, at about $10^{-6}$ s AG, a watershed has been reached. No longer can the quarks remain as a single, closely knit, cosmos-wide community. The density of matter has already become too low for that. Driven by their irrepressible need to remain always very near to at least some of their kind, the quarks separate into groups of three. Always three – three quarks or three antiquarks – an arrangement that seems to satisfy well their communal desire. Now, after the first one millionth of a second or so, and for all the rest of time, the universe will be devoid of "naked" quarks. Try to pluck one of its nucleonic bag and the attempt will be foiled. For each quark is like the end of the elastic thread of force that joins it to its neighbor. Can one end of a thread be made to exist on its own? No: Because in the attempt to isolate one end, the original thread is snapped in two, each new piece with its own pair of ends!

But now already our own quark has moved deeper into the past, back to a time when many of its kind still roamed free. Ever smaller dwindles the number of nascent nucleons and antinucleons as their contents break free to join the primal ocean of quarks all around.

A mere $10^{-8}$ s AG reads the time gauge. And now all protons and neutrons and their antiparticles are gone, leaving the universe replete with an inconceivably hot and dense consommé of leptons, photons, and quarks. Not one of these particles boasts any extension in space. Not one has the solidity or the apparent propensity for organization that matter in the future universe will have. And yet each of these spots of next-to-nothingness seems to "know" exactly what it is; even stranger, what its rules of engagement are with other particles. And that seems most peculiar. It seems to bring us close, in fact, to the very heart of what reality is. For now we are dealing not with stars, or rhinos, or political intrigue, or with any such higher level of complexity. One hundred millionth of a second after the universe began, we stand in the presence of near-ultimate simplicity.

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Ironic that something so simple should prove so enigmatic, so hard to understand. We thought we knew matter, knew it intuitively at least. Just as we believed we had an innate feel for those other rudimentaries of nature, energy, space, and time.

Matter was? Tangibility, substance. It was the ground beneath your feet, this book in your hands. And yet all that is now seen to involve a much more abstruse concept. What we experience and label as "matter" in our macroscopic world is actually some vastly elaborate and entangled hierarchy, as far removed from the basic underlying essence of matter as a Wagnerian opera is from each of its component notes.

Matter – raw, unembellished matter, the protocosmos reveals – consists of quarks and leptons. And nothing more. All there ever will be in the universe must be fashioned from these insubstantial parts. (The photons, too, are still present in huge numbers but are constituents of energy.)

But a quark and a lepton have no size. And yet, somehow, they must contrive to make "objects" that we perceive to have physical extension. Objects like you and me, and galaxies.

And there is more to this mystery of matter. Because, of course, the quarks and leptons of the early universe are not individually aware of the task ahead of them – that they have to come together to make neutrons and protons, atoms and molecules, stars and galaxies, and, eventually, cosmologists. Yet at $10^{-8}$ s AG they are also everything, materially, that there is. And from them, indeed, progressively more interesting creations will come.

Blind and primitive the dawn quarks and leptons may be. Yet they are destined for greater things. Though their febrile dance has the appearance of being chaotic, out of that chaos, we know, will emerge order. It is as if they carry within them a code, like a colossal genetic code, for building the universe to come.

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But building presupposes the ability to join parts together. So that not only must there be fundamental particles, but there must also be fundamental forces by which to bind them.

In chess, too, forces are at work. A chess piece "interacts" with another when it captures it. And there are several ways this may happen – several types of chess force. Certain of the pieces, for example, can strike from one or more squares away, an ability to capture we might describe as "long range." On the other hand, a piece such as the king, say, is limited to attacking its victims solely from an adjacent square, so that its influence is clearly more "short range." We could even go on to identify subcategories: a second kind of short-range force, for example, as exhibited by the pawn during en passant capture. The essential point, though, is this: Different chess pieces exert different types of force, which, in turn, are defined by the rules of the game.

And so it is with the cosmic chess game. In this case the governing laws, it turns out, prescribe four forces. Not eight, or twenty-two, or any other number, but precisely four: a quartet of natural forces that operates within the universe, one hundred millionth of a second after its formation, as it will for all the rest of time.

Of these cosmic forces two are long range, capable of acting over any distance. And for this reason they are the ones well known to us – gravity and electromagnetism. Gravity is the force that operates between all things in the universe with mass. Gravity, the planet builder, the apple dropper, the star crusher. But gravity, too, the incredibly feeble: Compare it with electromagnetism, that force which all electrically charged particles exert on one another. A pair of protons push apart more powerfully through electromagnetism than they pull together through gravitation by a factor of 100 million trillion trillion trillion! Only because, overall, space is electrically neutral does gravity come to dominate over cosmic scales.

At very much shorter range, when subatomic particles are in near contact, two other, totally unfamiliar forces may play their hand. These are the strong and the weak force: the strong, the strongest force of them all; the weak, ten trillion times feebler than electromagnetism, yet still awesomely large by gravity's standard.

Just as in chess, where not every piece may exert all of the forces that the game allows, so also in nature. An electron, for instance, can take part in interactions through gravity, electromagnetism, and the weak force, yet neither can it exert nor "feel" the strong force. The last is the reserve of the quarks.

So perhaps, indeed, the universe is merely a gigantic board game. It has pieces (particles), a board (space), and, apparently, its own set of rules (defining the particles and the ways they can interact). Presumably, it began with its pieces in some certain arrangement, the opening moves were made, and now the great cosmic game is underway.

Yet the analogy is far from perfect. And that for a very good reason: We can look beyond an actual chessboard to see the human hand that moves the pieces. We know why chess is the way it is, why it has its own ad hoc set of rules. We know because we devised it. We are the gods of chess who look down on it and control it and understand everything about it from our "meta-chess" world. But how can we say that of the entire universe? No convenient metacosmos exists to afford us a true god's-eye view (and if it did, we should need a metametacosmos from which to look down and understand that). Nor can we glimpse any obvious outside agency guiding each particle in space moment by moment. The universe seems to run itself, to make its own game moves from within.

As for the setting up of the cosmic board, and the devising of the cosmic game rules, here is the greatest puzzle of them all. For, like chess, the universe seems to have one set of rules, one set of pieces, one board. It exists in a certain way. One hundred millionth of a second after its birth, it contains just certain types of particle, able to interact through just a handful of specific forces. But why?

In the case of chess such arbitrariness is no mystery. We know chess to be a capricious product of the mind. We accept that its human inventors could as readily have compiled a quite different set of rules (some did and came up with checkers and Go).

But the contrived nature of the universe is not so easily understood. Who or what devised the cosmic rule book, laid down the great board of space, and set up the particle pieces? Why those rules, that board, those pieces? Why not, ten nanoseconds after the game began, a cosmos with seven different forces? Or none at all? Why not with a cosmic collection of pieces wholly unlike the quarks or leptons? And where did all this fantastic ensemble of matter and energy come from anyway?

Ever the wide-eyed child within us asks such questions, now as it did years ago: How did all this come about? What made the world? And why this world?

Ever the wise old scientist within us strives to reply, to reconcile and satisfy:

"I know the universe seems contrived. But since we're here discussing it all, it must exist in some state. And whatever state that happens to be is bound to appear special!

"At the same time, I understand your concern. 'Why,' you want to know, 'did the universe evolve in this way and not some other?' Just bear with me if you will. Because I believe I can fully answer that. My plan is to study the universe as it is now, just as I might examine the state of a chess game sometime after it has started. Then, once I have figured out all of the rules, I shall work backward, move by move, to deduce the original state of the game. Give me another ten, or fifty, or a hundred years and I'll have all the essential detail of the early universe worked out. I've every confidence I can push my way back to the moment of genesis itself. You wait and see."

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Now our time indicator shows $10^{-9}$ s AG. And the entire cosmos has shrunk so much that it would fit comfortably inside the globe of the future sun – a tiny womb wherein the most primitive forms of matter and energy incubate.

Deeper, ever deeper, our particle descends into the eye of the swirling vortex of counter clock time. To within one ten billionth of a second of creation it moves, while around it the temperature soars to ten thousand trillion degrees. And now another transition begins, more remarkable, more profound even than the freeing of the quarks from their nucleonic jails. Once again it is as if the universe had tripped some hidden mechanism, a mechanism seemingly precontrived and awaiting only the right time and conditions to set it off.

Four cosmic forces there had been: electromagnetism, gravity, the strong force, and the weak. Four basic ways in which the humblest particles in nature could interact. But now, at $10^{-10}$ s AG, an extraordinary change is starting to take place. Electromagnetism and the weak force, previously so disparate in character, are fast growing more and more alike. As the temperature rises further and time edges back to just one trillionth of a second AG, so these two forces gradually meld and become one. The product of their improbable union: the electroweak force.

(Again, it must be remembered, this is in time-reverse order, from future to past. So that in truth the universe started out, prior to $10^{-12}$ s AG, with three distinct forces. One of these, the electroweak, then began to fork. And thereafter its twin offshoots went their separate ways, never to reunite.)

Even so, the primal kinship of electromagnetism and the weak force would not be lost, just as in some future age man and the apes would diverge from common stock and yet still retain the evidence of their shared ancestry. That affinity, between life's evolution and the development of the early universe, runs deep. Both are marked unmistakably by the growth of complexity. Four forces from three. Compound particles from simple. Man and ape from a single, prehominoid ancestor. Revealed here is a common omnipresent urge of the cosmos to unfold, to progress, by its own efforts, toward some unseen final goal. This same urge it was that prompted both the splitting of the electroweak force and, billions of years later, the division of the line that led to man.

Yet how far back can this process of complication be traced? Are the three forces and the handful of elementary particle types in the universe at $10^{-12}$ s AG themselves the products of an even earlier chain of evolution? Or do they represent nature's ultimate, irreducible state?

Onward our quark explorer presses in quest of Time Zero, its energy increasing without bound as it penetrates farther into the past. Beyond $10^{-13}$, $10^{-14}$, $10^{-15}$ s AG, it goes, while around it the temperature and density of cosmic matter rise and rise to new inconceivable heights. Trillions of encounters it has, but always these involve the same triad of forces and the same basic set of rules.

Now, at $10^{-20}$ s AG on the exponential time scale, our particle has crossed more orders of magnitude than those that separate humans from the one-second-old universe. Even so, its immense, regressive journey into Deep Time has barely begun. Still, at $10^{-25}$ s AG, there is no sign of any further qualitative change. The separation of electromagnetism from the weak force now lies at an awesomely remote point in the future. Was it, after all, the first crucial cosmic development, the first-ever step toward great complexity?

And now, farther back our hero flies, to $10^{-35}$ s AG. Suddenly, with the universe ten trillion trillion trillionths of a second old, the question is answered. Just as before the electromagnetic and weak forces conjoined, so now, at this much earlier time, the strong force begins to merge with the electroweak. It is a stunning event – a triumphant triple alliance that brings to the universe, at last, an even simpler and more perfect order.

Now there are only two distinct ways in which any piece of cosmic matter may interact. There is gravity. And there is the grand unified force. Embraced by the latter are all of the attributes previously associated with the strong force and the weak and with electromagnetism. It is as if all the pieces on a chessboard – pawns, rooks, and bishops alike – were given the same freedom to move around and coact as a queen. How could any of the pieces then meaningfully be told apart? When the strong force united with the electroweak that same freedom was bestowed upon the quarks and leptons. Suddenly anything a quark could do a lepton could do equally well. A lepton could even turn into a quark, a quark into a lepton.

In this new democratic universe no longer is our hero particle distinguishable from any of the others with which it interacts. The differences between quarks and leptons, so conspicuous before, have vanished. They are revealed as having been mere facades, skin-deep variations, hiding a common core within.

Yet even as the universe assumes a form still simpler than before, the mystery of its origin and unfolding remain. At $10^{-35}$ s AG all that there is from which to build all there will ever be is this pocket sea of primitive, like particles – the quark-leptons. But what drove these cloned specks of energy to evolve and combine, through many branching levels of complication, into atoms and galaxies and minds? Despite their overt simplicity, the grand-unified particles bear – even at this early stage – the inner potential for what is to follow. Truly they are the spores of the cosmos, the harbingers of complexity to come. But even spores must have an origin, as must the concealed genetic message they carry.

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So, to the final stage of our assault on genesis. And now we must venture on alone, forsaking the company of the particle with which we have journeyed thus far. Already it is moving away from us, our last direct link with the cosmos we knew. For a while we watch it still, colliding, merging with its protagonists, then reasserting its individuality once more. And yet no longer can we really be sure whether this is "our" particle or some other that is identical to it in every sense.

So at last we turn away. And prepare our imagination – to accept a universe that has shriveled to the size of a pea. That has become so heated – to 100 trillion trillion degrees – that every particle within it has the energy of a charging bull. And that, like an equatorial dusk, is rapidly about to ...

Darken.

What a stunning, almost biblical, genesis it would have made – this, the brief, spectacular era of the creation of the particles. Here, at $10^{-35}$ s AG, or a little before, most of the matter in the universe, sprang into being. Photons too – explaining, in time reverse, the sudden dimming. As part of the process by which the strong force uncoupled from the electroweak, by which the grand unification was broken, most of the material that the universe would ever contain showered into existence.

And yet, surprisingly, this is not the true beginning. It may be the moment when the cosmic cast of matter first appeared. But before that there was still the empty, waiting stage – still space, still time, and, in some curious abstract form, still the laws that regulate every physical action, including the birth of matter. So we must search on to find now the source of the backdrop against which the particle actors will play out their drama. And we must search in the dark, groping, shedding what dim light we can by our own mind's eye.

Presently, with the distractions of matter gone, the very geometry of space and time begins to make itself apparent. Subtly woven together, it seems, space and time form a surface upon which all the events of the future universe may take place. And yet this topographic "space-time" is neither static nor necessarily flat like an artist's canvas. It can move – swell or contract – and it may warp and twist, even curve back upon itself to yield a closed shape like the surface of the Earth. But whereas the boundary of a normal sphere has only two dimensions and is curved in a third, the surface of space-time has, from the outset, an unimaginable dimensionality of four (three of space, one of time). And so any warping of it must involve a still more recondite, fifth dimension.

Only through some strangely heightened awareness – an ability to perceive more than three dimensions at once – are we able now to trace the further devolution of cosmic space and time. We "see" in n dimensions, where n is a number indefinitely high. But we are compelled to set down our impressions here, imperfectly, in just three. At $10^{-40}$ s AG the universe is the surface – so we imagine – of a microscopic ball, still shrinking.

In speculative vision we see the ball-universe from outside, a faintly glowing orb suspended in blackness. The chronometer reading is $10^{-41}$ s AG. Far smaller than a proton now is the vacant, embryonic cosmos; we, circling around it somehow, occasionally swooping in to view more closely the texture of its space-time skin. Smooth and continuous this had seemed at first. But now, at $10^{-42}$ s AG, the first signs of a less than perfect complexion are beginning to appear. The surface of the ball-universe, near to, looks finely speckled. And the speckles are dancing, vibrating chaotically like a swarming mass of flies.

So in this myth within a myth is the motile graininess of space-time itself revealed to us. But even at that instant of discovery – our chronometer marking the time at $10^{-43}$ s AG – we are overwhelmed by a far greater surprise. Rising up to meet the tiny, luminous drop that is our nascent universe is a tall, slender, shimmering spire. And as in bewilderment we look down this, from the tip of its needle like summit, down its sheer sides, to the gentler sloping curves of its base, we see that it is itself merely a trivial and temporary feature thrown up from a vast, turbulent ocean of pandimensional space-time. With sudden, terrible insight we realize that our cosmos is like an insignificant speck of foam that has escaped from the endless, restless sea. Escaped, sealed itself off, grown, nurtured a hundred billion galaxies, and . . .

A speck of foam that is now becoming stretched into a tear-shape, to be re-joined, as we see it in retrospect, with its cosmic mother sea. The spire makes contact, fuses at its tip with the errant droplet, then descends with its long-lost prize back into the froth and spume below.

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Shocked by the suddenly, brutally widened horizons of our vision, we slam shut our cosmic senses. This must be some crazed dream or a fantasy brought on by overzealous imagining. And yet:

"It is neither," urges the familiar voice of the scientist within. "Simply, you have been witness to one of my more engaging reconstructions of genesis. Allow me to explain.

"As you watched our universe approach the actual moment of its birth, the previously hidden, inner structure of space and time came into view. You began to see the elaborate, shifting microarchitecture of space-time. When, finally, the time intervals you could discern were as small as $10^{-43}$ of a second, the characteristic lengths no greater than $10^{-32}$ of an inch, the full evanescence of the cosmic fabric became clear. At these scales the very concept of distance and duration loses meaning. Tiny new regions of space and time can spring capriciously into existence or, just as readily, die out.

"One of these regions, by chance, broke free from the great primordial sea of space-time – and, in due course, evolved into the cosmos you know. The instant at which it detached itself from that slender, rising stem – the instant it became an independent 'child universe'–

was, if you will, Time Zero, the moment of genesis. It was then that the internal clock of our universe began to tick.

"As for the parent ocean of space and time from which our cosmos arose, I can say little. It was a confused region, devoid of stable or specific dimensionality. Perhaps, in truth, it was less like an ocean, more of a fine dust – a pregeometric dust of points, outside of space and time, that occasionally and locally assembled itself to make the seeds of future universe."

And yet that leaves much unanswered: If this "ocean" or "dust" existed outside of space and time – if it was, in some sense, the basal stuff from which organized space-time could come – how then could it change? How could our universe have been "ejected" like a speck of foam from the precosmic ocean? Or, invoking the other metaphor, how it could it have been "assembled" from a collection of points in the ancestral dust? Whether the progenitor of our universe was like a wind-lashed sea or a swirling, ethereal dust of pregeometric particles, if it existed outside of time, then how could it alter, reconfigure itself, so as to spawn a coherent, self-sufficient universe? Change of any sort, however esoteric, however unimaginable, demands the prior existence of time. But then where did time come from?

"Yes, I know there are some small details missing. But, you see, all this is such a new field of research. We've barely scratched the surface of the science of genesis. To have tentatively reached back to within just $10^{-43}$ of a second of creation, to have begun to address the problem of the origin of space and time itself, is – you must concede – no mean accomplishment."

True. Science has achieved much, and it will go on to achieve much, much more. Yet, nevertheless, it is working back along an exponential scale. And before $10^{-43}$ s AG came $10^{-44}$ s AG. And before that $10^{-45}$ s AG. Maybe when physics is a century older we shall have a rationally arrived-at account of what $10^{-100}$ s AG was like, or even $10^{-1000}$ s AG, if such times have any physical meaning. Yet still left unsolved will be the mystery of "what came first?" And, in some ways, that is really the only question that matters.

"Ah! I think you're assuming now that there must have been some initial cause of our universe. But in fact, when we probe closely the world of the very small, we find that there's no such simple chain of cause and effect. Particles of matter and energy and – our recent theories tell us – of space and time, too, behave unpredictably. They can appear and disappear, without prompting, without prior intervention. And if they can do that . . . well, it seems entirely reasonably – even quite likely – that the universe itself may have begun as a chance event.

"Exactly what it 'began from' is still, I confess, a moot point. I conjured up the ideas of a natal ocean or a dust cloud. But of course I don't mean you to take these too literally. At best they are devices to help your mind key upon the extraordinary problem of cosmic origins. As soon as you are able to, and if you so wish, cast the devices aside. Do without the crutch of believing there was 'something' there to begin with, a nebulous, indefinable matrix from part of which our universe took shape.

"Instead of that 'something,' suppose there was, quite simply, nothing. And I do mean, no-thing – neither space nor time. Then, by chance, there was a fluctuation. Maybe there were many of them, but only one persisted. It was a fluctuation – a tiny, random, unmotivated flutter – in which a pattern of points appeared. Those points constituted, by their type and arrangement, a primitive space-time. Our space-time. The arrangement proved stable. And so it endured. Not only that but, in time, it evolved – evolved so that regions of it became intelligent and, eventually, curious about their cosmic origins.

"And there you have it. My greatest, most daring speculation – the universe sprang into being, purely by chance, out of a perfect, spaceless, timeless vacuum."

Creation ex nihilo! The supreme scientific myth . . .

Except that it is fatally flawed.

Space and time never could just "spring into being," because measured against what time order would they do the springing? Detail is absolutely crucial here. There can bo no fudging the issue, no playing with words, no leaps of faith. Exactly how could time (or space, for that matter) begin? Describe the process. Describe the very first step.

And now the scientist within is silent. For the unassailable fact is this: Under no circumstances can there have been a time when time did not exist! Never a state of timelessness.

And what applies to time applies equally well to the laws of the universe. There can never have been a time – a pretemporal state – of lawlessness. Because otherwise by what design or mechanism could the laws have been produced? And so carefully, so uniquely selected?

Science has come far, led us almost to the summit of our cosmic mountain, almost to the source of our universal stream of space and time, of matter and energy. Almost. But in the process of seeking out the headwaters of all creation it has confined itself – perhaps necessarily – to reductionism. And so now the scientist-priests in their search for genesis appear like folk on their hands and knees peering within the tiniest crevices around Time Zero for that legendary inaugural event, the primum mobile. If only they can rid themselves, so they think, of the last vestige of time and space and materiality. If only they can show that, in the beginning, there was simply this most perfect, pristine nothingness. And if only they can demonstrate that from this inconceivable absence of anything the plenum of existence naturally, fortuitously flowed – then they will have succeeded.

Nor should we criticize. For reductionism indeed has borne rich fruits of understanding. This whole epic journey through Deep Time is, in part, a celebration of what science has discovered or conjectured about where the cosmos came from and where it is going.

But to grasp the ultimate truth of genesis – that requires an abrupt change of perspective, a new scientific and philosophical outlook, or maybe a radical expansion of the old. For now we must look not to reductionism but to holism. Not obsessively at one certain point in the universe, but at all the universe, future as well as past. And why? Because, as we are dimly now beginning to see, the creation of the universe was in some curious way bound up intimately with what was to come.

The cosmos was not – never could have been – some accidental flower that grew spontaneously from a nothing speed. Its galaxies and earthly flowers and blossoming, self-aware minds are not mere lucky inventions. The universe is exquisitely designed, intelligently constructed, beautiful beyond belief, a creature spawned out of awesome complexity, not austere simplicity.

And now, suddenly, our task becomes clear. It is to search for the source and meaning of the cosmos not in the extreme past but, on the contrary, in the remote future – at the nether edge of Deep Time.

# Chapter 3: Kinds of Flowers

*The most beautiful experience we have is the mysterious.*
*It is the fundamental emotion that stands at the*
*cradle of true art and true science.*
– Albert Einstein

Already fading are those strange, shifting impressions of Time Zero, those half-glimpsed images culled from the scientific lore of genesis. With a single instantaneous leap we have returned to a more familiar place: the one-second-old cosmos, with its thick, pervasive stew of protons, neutrons, electrons, photons, and neutrinos, simmering at ten billion degrees.

From this point a new phase of our adventure begins. Inevitably, mysteriously, the path to the future winds away into the gray, misty distance. And even as we strain to see where it may lead, our particle hero, restored to its protonic form, approaches once more out of the bright chaos around.

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Urgently, unpredictably, our proton moves, as of old, from one brief encounter to the next. Rebounding from an electron, now from a fellow proton, it seems engaged in an endless, apparently aimless game of subatomic billiards.

Not for the last time do we ponder the prospects for this mad jumble. And yet we recall, too, that the universe has already passed through a bewildering series of transformations – in a single second! So how much more might it not evolve in the billions upon billions of years to come?

Still, factored in must be the rate of cosmic metamorphosis. And that now is noticeably on the wane. The next ten seconds bring no fresh revolution, no great new surprise. At the fifteen-second mark, though the temperature has dropped to a balmy three billion degrees, the particle mix remains the same.

A full minute goes by. And more. So that, half seriously, we begin to doubt whether nature has any creative power left following the first frenetic second.

Two minutes AG. Three minutes. (The doubt grows.) Three minutes 45 seconds AG:

And now, as it has many times before, our proton draws near to another tiny islet of matter – a neutron – collides with it, and scatters. Yet, for a lingering instant, the proton and neutron remain attached. Like two drops of liquid that touch, the nucleons momentarily fuse. Only barely is the vigor of their impact enough to prevent the strong nuclear force – operating between the proton and neutron at close range – from binding the two particles permanently together.

But even as our proton flies off, its independence narrowly preserved, the neutron from which it has just pulled free strikes another proton nearby. And this time there is no subsequent scattering. Instead, the neutron and its new partner remain tightly, securely bound together – as a nucleus of deuterium, or heavy hydrogen ($H^2$).

At last, it seems, the temperature has fallen sufficiently for this new stage of cosmic synthesis to begin. Alongside those most primitive of nuclei, the protons (the nuclei of ordinary hydrogen), small quantities of deuterium start to appear. And not only that. Some deuterium nuclei quickly go on to collide with and absorb an additional neutron and thereby change into tritium ($H^3$), the heaviest form of hydrogen. Others, by chance, acquire an extra proton and so transmute into a lightweight variety of helium, helium 3. In either case the normal mode of helium is but a short step away. Tritium swallows a proton and becomes helium 4 (two protons plus two neutrons); helium 3 swallows a neutron and does the same.

At three and three-quarter minutes AG vast quantities of helium 4 are being produced rapidly all over the universe. And yet therein lies a puzzle. For the fact is that helium 4 is sturdy enough to survive at temperatures of around three billion degrees. In other words, it was sufficiently cool much earlier, at only fifteen seconds AG, for ordinary helium to exist. Why then did it take so long to appear?

The answer lies with the temperature stability of the middlemen: deuterium, tritium, and helium 3 – especially deuterium. Three billion degrees is still far too hot for these weaker-bound nuclei to hold together, so that they are simply blown apart the instant they form. Although the end product, helium 4 is stable at much higher temperatures, its formation is delayed by the more fragile nature of its intermediaries.

Only as the temperature slides down to around 900 million degrees, at about 225 seconds, do deuterium and tritium and helium 3 each manage to cling together long enough for the final jump to helium 4 to occur. And then, quite suddenly, it happens: The universe is 10 percent helium, and the dramatic moment passes at which deuterium finally achieves stability. With the chain reaction process from individual neutrons and protons to helium 4 no longer chocked off at the second level (deuterium), virtually all the remaining free neutrons are gobbled up into helium nuclei.

And our proton? Despite some close shaves, it has retained its liberty throughout this early phase of cosmic nucleosynthesis. Though one in ten of the nuclei around it are now of helium 4, almost all the remainder are free protons like itself. A tiny fraction endure as deuterium and helium 3 (though not as tritium, since this is radioactive and quickly breaks up). And there is a small but dwindling tribe of nomadic neutrons.

Unlike the proton, the neutron cannot live indefinitely on its own. Bound up within a nucleus, it is secure. But alone, unattached, it must, as if it were a live grenade, quickly split apart – another strange idiosyncrasy of nature. Isolate any neutron at random and the chances are fifty-fifty that it will decay – into a proton, an electron, and an antineutrino – within just twelve minutes. Every 100 seconds from now on the remaining population of free neutrons will decline by 10 percent, until the only neutrons remaining will be those enclosed within nuclei.

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Four minutes after the Big Bang: Blindingly intense radiation bathes every corner of space. The photons swarm, 100 million of them for every proton and neutron. Electrons and their antiparticles, the positrons, continue their inevitable annihilation, until all the positrons have gone and the residual electrons are roughly equal in number to the protons. There are the ghostly neutrinos and antineutrinos. And, at the other extreme of materiality, there is this new, complex thing called helium.

But why should the universe stop at the helium stage? Why not go on immediately to build still more complicated nuclei, perhaps those of carbon, oxygen, silicon, or even iron? The reason is the same as that for which the formation of helium 4 was delayed. Even when the final product was stable, certain intermediate nuclei – vital stepping-stones in the process of nucleosynthesis – were still highly unstable. Deuterium's temperature sensitivity caused the hold-up in helium 4 manufacture. Now, for anything heavier than helium, such as lithium 6, beryllium 9, boron 10, or carbon 12, it is the unstable nuclei with five and eight nuclear particles that are the stumbling block. Only in a very different environment, in the dense, central furnaces of stars-to-come, will nuclei more elaborate than helium be able to take shape.

A half hour slips by. Our proton moves within a cosmos cooled to 300 million degrees – just fifteen times hotter than the core of the future sun. Less often now does it collide with other particles. The average density of matter has dropped to just one tenth that of water. Nucleosynthesis has come to a virtual standstill.

And again there is apparent quiescence. Again, after a sudden, frenzied burst of change and synthesis, the anxious waiting for some new, unknown step toward greater cosmic complexity. Only this time the waiting seems longer – interminably long, even by human standards.

Gone forever is the Golden Age of ultrafast transition, when the character of the whole universe could alter beyond recognition within the smallest fraction of a second, or within a few seconds, or a few minutes.

An hour elapses. A day. A year.

A thousand years!

And, all the while, space relentlessly expands, stretching further the kinetic pattern on its multidimensional surface. The density of cosmic matter, along with its temperature, continues steadily to fall. And yet, apparently, there is no change in matter's quality.

Ten thousand years go by. And even though our proton, like the countless other protons and heavier nuclei around it, often passes close to an electron, it forms no partnership with it. Even though the proton and electron have equal and opposite charge, and are therefore powerfully drawn to one another, they fail to come together in stable alliance. X-ray and ultraviolet photons – bullets of high-grade energy – strafe the fledgling cosmos, instantly stripping away any electrons that dare to enter bound states around a nucleus. Laser-intense, ubiquitous, the young electromagnetic field tears apart anything resembling an atom. And so, for millennia upon millennia, while the universe burns this bright, there is only a writhing, thinning, electrically charged mist – a plasma – of loose nuclei and electrons.

Or so it had seemed. And yet there may be more to this young universe than simply a hot, spreading fog of particles and blazing light. For now the saga of our proton is beginning to take a strange new turn. And the prospect is slowly emerging that there may have been other things born of the Big Bang, bizarre, almost indescribable things, that have surreptitiously found their way into nature.

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At first it had seemed incredible. But now there can no longer be any doubt. Our proton is being pulled, gradually, irresistibly, over thousands of years, toward ... what? Some unknown attractor. An obscure but tremendously powerful source of gravity. And it is not just our own tiny particle but all of the subatomic matter for light-years around that is streaming in toward this unnamed, previously unsuspected phenomenon. Nor is the mystery attractor unique. There are billions of others of its kind strewn about space, each busily spinning its own cocoon of hot plasma. Evidently, even as the universe continues its headlong outward rush, portions of it are being drawn together locally. Material is steadily accumulating around