Was There a Big Bang?

David Berlinski

SCIENCE IS a congeries of great quests, and cosmology is the grandest of the great quests. Taking as its province the universe as a whole, cosmology addresses the old, the ineradicable questions about space and time, nature and destiny. It is not a subject for the tame or the timid.

For the first half of the 20th century, cosmology remained a discipline apart, as a clutch of talented but otherworldly physicists peeped inconclusively at a universe they could barely see: Albert Einstein, of course; the Dutch mathematician Willem de Sitter; the Belgian abbot Georges Lemaître; and the extraordinary Russian mathematician and meteorologist Aleksandr Friedmann, destined to die young, or so the story has it, from exposure to the elements suffered while soaring above Moscow in a weather balloon.

When in 1917 Einstein published his first estimates of the size and shape of the universe, telescopes could not penetrate the heavens beyond the Milky Way. Like a sailor endeavoring to measure the depth of the sea from the shore, astronomers lacked the means to probe the heavens further or to probe them in detail.

This has now changed. Information pours from the night skies, terrestrial telescopes hissing and clicking as they rotate to survey distant galaxies. Somewhere in space, the realigned Hubble telescope peers into the unpolluted depths. Physicists have pictures of the backside of beyond, and they appear to have overheard the cosmic cackle that accompanied the very crack of time, as nothingness gave way to light. The cosmologists have come into their own, handling the universe with an easy familiarity and writing book after book in which they explain in exuberant detail how the great things were done.

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The Great Cause

WHATEVER THE dreams we dream, the existence of the universe has always seemed a riddle beyond reason, if only because our imagination is forever suspended between ideas of creation and timelessness. Many ancient myths depict the universe as the effect of some Great Cause. In the Babylonian epic *Enuma Elish*, existence is attributed to congress between "primordial Aspu, the Begetter" and "Mummu-Tiamet, she who bore them all." Although the connection cosmic and sexual energies is both familiar and disturbing, it is not congress between gods that is crucial to the myth but the idea that the universe came into being as the result of a Great Cause. And this idea is conveyed by the opening of Genesis as well: "In the beginning, God created the heavens and the earth."

These are words that express an authentically universal concept, one familiar to every culture. But while the concept of creation is common, it is also incoherent. "I venture to ask," the 3rd-century Chinese sage Kuo Hsiang ventured to ask, "whether the Creator is or is not. If He is not, how can He create things? And if He is, then (being one of these things) He is incapable (without self-creation) of creating the mass of bodily forms." That this argument is simple is no reason to think it wrong.

If not creation by a Great Cause, what, then, of timelessness: a universe proceeding sedately from everlasting to everlasting? In Maori myth, the world parents who bring the cosmos into being arise themselves from *po*, a kind of antecedent gruel or stuff, so that the universe appears as an episode in an infinitely extended drama. Some variant of this idea is also universal, a place in every culture where the weary mind takes refuge. Yet if timelessness offers an escape from the paradoxes of creation, the escape can easily seem an evasion. An everlasting universe is itself an object requiring explanation: if it is unprofitable to ask *when* it arose, one nonetheless wonders why the damn thing should be there at all.

It is the remarkable claim of contemporary cosmology to have broken, and broken decisively, the restless movement of the mind as it passes from theory to theory and from myth to myth. "Incomplete though it may be," one physicist has written, "the scope of modern scientific understanding of the cosmos is truly dazzling." This is not hyperbole. It is an assessment widely shared among physicists, and thus the standard by which their claims must be judged.

The universe, cosmologists now affirm, came into existence as the expression of an explosion, the cosmos shaking itself into existence from the bang of an initial singularity. It is tempting to think of the event in humanly comprehensible terms—a *gigantic* explosion or a *stupendous* eruption, as if, popcorn in hand, we were watching the show from far away. But this is absurd. The Big Bang was not an event taking place at a time or in a place. Space and time were themselves created by the Big Bang, the measure along with the measured.

As far as most physicists are concerned, the Big Bang is now a part of the structure of serene indubitability created by modern physics, an event undeniable as the volcanic explosion at Krakatoa. From time to time, it is true, the astrophysical journals report the failure of observation to confirm the grand design. It hardly matters. The physicists have not only persuaded themselves of the merits of Big Bang cosmology, they have persuaded everyone else as well. The Big Bang has come to signify virtually a universal creed; men and women who know nothing of cosmology are convinced that the rumble of creation lies within reach of their collective memory.

The Cosmic Archeologist

Looking at a few shards of pottery on the desert floor, the archeologist is capable of conjuring up the hanging gardens of the past, the smell of myrrh and honey in the air. His is an act of intellectual reconstruction, one made poignant by the fact that the civilization from which the artifacts spring lies forever beyond the reach of anything but remembrance and the imagination. Cosmology on the grand scale is another form of archeology; the history of the cosmos reveals itself in layers, like the strata of an ancient city.

The world of human artifacts makes sense against the assumption of a continuous human culture. The universe is something else: an old, eerie place with no continuous culture available to enable us to make sense of what we see. It is the hypothesis that the universe is *expanding* that has given cosmologists a unique degree of confidence as they climb down the cliffs of time.

A universe that is expanding is a universe with a clear path into the past. If things are now far apart, they must at one point have been close together; and if things were once close together, they must at one point have been *hotter* than they are now, the contraction of space acting to compress its constituents like a vise, and so increase their energy. The retreat into the past ends at an initial singularity, a state in which material particles are at *no* distance from each other and the temperature, density, and curvature of the universe are infinite.

The cosmic archeologist may now be observed crawling back up the cliffs of time he so recently descended. During the first 10^{-43} seconds after the Big Bang—10^{-43} is one over a ten followed by 42 zeros—both matter and radiation fill the void. A reign of fluid interchange obtains, with particles of matter and antimatter exchanging identities. As the primitive goo of the cosmos—what the physicist George Gamow called *ylem*, the primordial stuff—continues to expand, it continues to cool. Neutrinos, photons, electrons, positrons, neutrons, and protons agitate themselves throughout space. With the temperature dropping, the neutrinos decamp for parts unknown.

At roughly one-and-one-half seconds after the Big Bang, protons and neutrons lose the ability to exchange identities, and the ratio of neutrons to

protons in the universe freezes itself at one to six. Three-and-one-half seconds later, the equilibrium between electrons and positrons collapses, and the positrons follow the neutrinos into the void.

Three minutes pass. The era of nucleosynthesis begins thereafter. Those neutrons that during the freeze-out found themselves bound to the world's vagrant protons now take up an identity as a form of helium. Other elements wait patiently for the stars to be born so that they may be cooked in their interiors.

The universe continues to expand, pulse, glow, throb, and moan for 400,000 years more, passing insensibly from a place where radiation predominates to an arena where matter has taken charge and is in command. The temperature is now 4,000 degrees Kelvin. The great era of *recombination* is at hand, a burst of cosmic creativity recorded in the walls of time. Free electrons and protons form hydrogen. The interaction between matter and radiation changes dramatically.

Until recombination, photons found themselves trapped within a cosmic pinball machine, ricocheting from one free charged particle to another, the cosmos frustratingly opaque because frustratingly dense. But hydrogen binds the cosmic debris, and for the first time, light streams from one side of creation to the other. The early universe fills with low-temperature blackbody radiation, the stuff destined to be observed fifteen billion years later in Princeton, New Jersey, as cosmic background radiation (CBR).

The separation of light and matter allows the galaxies to form, gravity binding the drifting dust in space. At last, the universe fills with matter, the stars settling into the sky, the far-flung suns radiating energy, the galaxies spreading themselves throughout the heavens. On the earth that has been newly made, living things shamble out of the warm oceans, the cosmic archeologist himself finally clambering over the lip of time to survey the scene and take notes on all that has occurred.

Such is the standard version of hot Big Bang cosmology—"hot" in contrast to scenarios in which the universe is cold, and "Big Bang" in contrast to various steady-state cosmologies in which nothing ever begins and nothing ever quite ends. It may seem that this archeological scenario leaves unanswered the question of *how* the show started and merely describes the consequences of some Great Cause that it cannot specify and does not comprehend. But really the question of how the show started answers itself: before the Big Bang there was nothing. *Darkness was upon the face of the deep.*

Blow-Up

NOTWITHSTANDING THE investment made by the scientific community and the general public in contemporary cosmology, a suspicion lingers that matters do not sum up as they should. Cosmologists write as if they are quite certain of the Big Bang, yet, within the last decade, they have found it necessary to augment the standard view by means of various new theories. These schemes are meant to solve problems that cosmologists were never at pains to acknowledge, so that today they are somewhat in the position of a physician reporting both that his patient has not been ill and that he has been successfully revived.

The details are instructive. It is often said, for example, that the physicists Arno Penzias and Robert Wilson observed the remnants of the Big Bang when in 1962 they detected, by means of a hum in their equipment, a signal in the night sky they could not explain. This is not quite correct. What Penzias and Wilson *observed* was simply the same irritating and ineradicable noise that has been a feature of every electrical appliance I have ever owned. What theoreticians like Robert Dicke *inferred* was something else: a connection between that cackle and the cosmic background radiation released into the universe after the era of recombination.

The cosmic hum is real enough, and so, too, is the fact that the universe is bathed in background radiation. But the era of recombination is a shimmer by the doors of theory, something known indirectly and only by means of its effects. And therein lies a puzzle. Although Big Bang cosmology does predict that the universe should be bathed in a milky film of radiation, it makes no predictions about the uniformity of its temperature. Yet, looking at the sky in every direction, cosmologists have discovered that the CBR has the same temperature, to an accuracy of one part in 100,000.

Why should this be so? CBR filled the universe some 400,000 years after the Big Bang; if its temperature thereafter is utterly and entirely the same, some physical agency must have brought this about. But by the time of recombination, the Big Bang had blown up the universe to a diameter of 90,000,000 light years. A physical signal—a light beam, say—sent hustling into the cosmos at Time Zero would, a mere 400,000 years later, be hustling still; by far the greater part of the universe would be untouched by its radiance, and so uninfluenced by the news that it carried. Since, by Einstein's theory of special relativity, nothing can travel faster than light itself, it fol-

lows that no physical agency would have had time enough to establish the homogeneity of the CBR, which appears in Big Bang cosmology as an arbitrary feature of the early universe, something that must be assumed and is not explained.

THEORIES OF *inflation* now make a useful appearance. Their animating idea represents a contribution to cosmology from particle physics—a rare example of intellectual lend-lease, and evidence that disciplines dealing with the smallest of objects may be relevant to disciplines dealing with the largest. Within what is now known as the Standard Model, the familiar arrangement in which elementary particles are moved by various forces gives way to a mathematically more general scheme in which fields replace both particles and forces as essential theoretical structures. A field is an expanse or expression of space, something like a surface in two dimensions, or the atmosphere in three, or space and time in four. The Standard Model in particle physics consists of a dozen or so fields, exchanging energy with one another and subsidizing particles by means of the energy they contain.

It is the Higgs field that originally came to play a novel role in Big Bang cosmology. Named after Peter Higgs, the Scottish physicist who charmed it into existence, the Higgs field is purely a conjectured object. Its cosmological potential was first noted by a young American physicist, Alan Guth.

Fields are structures that carry latent energy even under conditions in which the space they control is to all intents and purposes empty. The natural and stable state of the Higgs field is one in which its latent energy is at a minimum. Such is its true vacuum state, the word "vacuum" indicating that the field is empty, and the word "true" that the field is in its lowest energy configuration. But under certain physically possible circumstances, the Higgs field can find itself adventitiously trapped in a *false* vacuum state, a condition in which, like a spring, it is loaded with potential energy. It is thus, Guth conjectured, that the Higgs field might have found itself fluttering about the early universe, energetically throbbing and dying to be of use.

The wish is father to the act. The energy within the Higgs field is repulsive: it pushes things apart. When released, it contributes a massive jolt to the process of cosmic expansion already under way. The universe very quickly doubles in size. Space and time stretch themselves out. Particles zoom from one another. If the ordinary course of cosmic expansion is linear, inflationary expansion is exponential, like the gaunt, hollow-eyed guest gobbling the hors d'oeuvres—and everything else—at a previously decorous cocktail party. Only as the Higgs field tumbles down to its true vacuum state does inflation come to a halt, and the ordinary course of the Big Bang resume.

The mechanism of inflation, cosmologists cheerfully admit, is rather like one of those Rube Goldberg contraptions in which a door is made to open by means of a sequence that includes a flashing neon light, an insulting message in a bottle, a prizefighter wearing patent-leather shoes, and a boa constrictor with an aversion to milk. Nonetheless, they add, inflation provides a natural and plausible explanation for the fact that the CBR is uniform in temperature. If the universe under standard Big Bang cosmology is too large to allow a coordinating physical signal to reach every part of the CBR, then one redemptive idea is to cast around for a universe smaller than the standard one. This, inflation provides. Within an inflationary universe, the CBR owes its uniform temperature to the fact that it has been thoroughly mixed. At the end of the era of recombination, the CBR then surges through space like pre-warmed soup.

Inflation is an idea that has gripped the community of cosmologists. Whether it has advanced their scientific agenda is another question. As we have seen, standard Big Bang cosmology requires that features of the early universe such as the temperature of the CBR be set arbitrarily. This has seemed intellectually repugnant to many physicists: the goal of science is to reduce the arbitrariness of description. But inflationary cosmology has arbitrary features of its own, which, displaced from one corner of the theory, have a habit of popping up in another. "The need for fine-tuning of the universe," the physicist David Lindley observed of Guth's proposal, "has been obviated by fine-tuning the Higgs mechanism instead." So it has.

Soon after its introduction, Guth's model of inflation required adjustment. The Higgs field has been replaced by scalar fields, which, as Guth admits, "in many cases serve no function other than the driving of inflation." These fields must be carefully chosen if they are to do their work, a fact that Guth again honestly acknowledges: "Their nature cannot be deduced from known physics, and their detailed properties have to be hypothesized."

In an interesting example of inflationary theory self-applied, inflationary fields have undergone an exponential increase of their own. Beyond mere inflation, the sort of thing that with great heartiness simply blows the universe up, there is chaotic inflation and even "eternal inflation," both of them the creations of the cosmologist Andrei Linde. Almost

all cosmologists have a favored scheme; when not advancing their own, they occupy themselves enumerating the deficiencies of the others.

Red Stars at Night

STREAMING IN from space, light reaches the earth like a river rich in information, the stars in the sky having inscribed strange and secret messages on its undulations. The universe is very large, light has always whispered; the nearest galaxy to our own—Andromeda—is more than two million light years away. But the universe has also seemed relatively static, and this, too, light suggests, the stars appearing where they have always appeared, the familiar dogs and bears and girdled archers of the constellations making their appointed rounds in the sky each night.

More than anything else, it is this impression that Big Bang cosmology rejects. The cool gray universe, current dogma holds, is a place of extraordinary violence, the galaxies receding from one another, the skin of creation stretching at every spot in space, the whole colossal structure blasting apart with terrible force. And this message is inscribed in light as well.

In one of its incarnations, light represents an undulation of the electromagnetic field; its source is the excitable atom itself, with electrons bouncing from one orbit to another and releasing energy as a result. Each atom has a spectral signature, a distinctive electromagnetic frequency. The light that streams in from space thus reveals something about the composition of the galaxies from which it was sent.

In the 1920's, the characteristic signature of hydrogen was detected in various far-flung galaxies. And then an odd discovery was made. Examining a very small sample of twenty or so galaxies, the American astronomer V. M. Slipher observed that the frequency of the hydrogen they sent into space was shifted to the red portion of the spectrum. It was an extraordinary observation, achieved by means of primitive equipment. Using a far more sophisticated telescope, Edwin Hubble made the same discovery in the late 1920's after Slipher had (foolishly) turned his attention elsewhere.

The galactic redshift, Hubble realized, was an exceptionally vivid cosmic clue, a bit of evidence from far away and long ago, and like all clues its value lay in the questions it prompted. Why should galactic light be shifted to the red and not the blue portions of the spectrum? Why, for that matter, should it be shifted at all?

An invigorating stab in the dark now followed. The pitch of a siren is altered as a police car disappears down the street, the sound waves carrying the noise stretched by the speed of the car itself. This is the familiar Doppler effect. Something similar, Hubble conjectured, might explain the redshift of the galaxies, with the distortions in their spectral signature arising as a reflection of their recessional velocity as they disappeared into the depths.

Observations and inferences resolved themselves into a quantitative relationship. The redshift of a galaxy, cosmologists affirm, and so its recessional velocity, is proportional to its distance and inversely proportional to its apparent brightness or flux. The relationship is known as Hubble's law, even though Hubble himself regarded the facts at his disposal with skepticism.

Hubble's law anchors Big Bang cosmology to the real world. Many astronomers have persuaded themselves that the law represents an observation, almost as if, peering through his telescope, Hubble had noticed the galaxies zooming off into the far distance. This is nonsense. Hubble's law consolidates a number of very plausible intellectual steps. The light streaming in from space is relieved of its secrets by means of ordinary and familiar facts, but even after the facts are admitted into evidence, the relationship among the redshift of the galaxies, their recessional velocity, and their distance represents a complicated inference, an intellectual leap.

THE BIG BANG rests on the hypothesis that the universe is expanding, and in the end the plausibility of its claims will depend on whether the universe *is* expanding. Astronomers can indeed point to places in the sky where the redshift of the galaxies appears to be a linear function of their distance. But in astrophysics, as in evolutionary biology, it is failure rather than success that is of significance. The astrophysical literature contains interesting and disturbing evidence that the linear relationship at the heart of Hubble's law by no means describes the facts fully.

At the end of World War II, astronomers discovered places in the sky where charged particles moving in a magnetic field sent out strong signals in the radio portion of the spectrum. Twenty years later, Alan Sandage and Thomas Mathews identified the source of such signals with optically discernible points in space. These are the quasars—*quasi stellar radio sources.*

Quasars have played a singular role in astrophysics. In the mid-1960's, Maarten Schmidt discovered that their spectral lines were shifted massively to the red. If Hubble's law were correct,

quasars should be impossibly far away, hurtling themselves into oblivion at the far edge of space and time. But for more than a decade, the American astronomer Halton Arp has drawn the attention of the astronomical community to places in the sky where the expected relationship between redshift and distance simply fails. Embarrassingly enough, many quasars seem bound to nearby galaxies. The results are in plain sight: there on the photographic plate is the smudged record of a galaxy, and there next to it is a quasar, the points of light lined up and looking for all the world as if they were equally luminous.

These observations do not comport with standard Big Bang cosmology. If quasars have very large redshifts, they must (according to Hubble's law) be very far away; if they *seem* nearby, then either they must be fantastically luminous or their redshift has not been derived from their velocity. The tight tidy series of inferences that has gone into Big Bang cosmology, like leverage in commodity trading, works beautifully in reverse, physicists like speculators finding their expectations canceled by the very processes they had hoped to exploit.

Acknowledging the difficulty, some theoreticians have proposed that quasars have been caught in the process of evolution. Others have scrupled at Arp's statistics. Still others have claimed that his samples are too small, although they have claimed this for every sample presented and will no doubt continue to claim this when the samples number in the billions. But whatever the excuses, a great many cosmologists recognize that quasars mark a point where the otherwise silky surface of cosmological evidence encounters a snag.

WITHIN ANY scientific discipline, bad news must come in battalions before it is taken seriously. Cosmologists can point to any number of cases in which disconcerting evidence has resolved itself in their favor; a decision to regard the quasars with a watchful indifference is not necessarily irrational. The galaxies are another matter. They are central to Hubble's law; it is within the context of galactic observation that the crucial observational evidence for the Big Bang must be found or forged.

The battalions now begin to fill. The American mathematician I.E. Segal and his associates have studied the evidence for galactic recessional velocity over the course of twenty years, with results that are sharply at odds with predictions of Big Bang cosmology. Segal is a distinguished, indeed a great mathematician, one of the creators of modern function theory and a member of the National Academy of Sciences. He has incurred the indignation of the astrophysical community by suggesting broadly that their standards of statistical rigor would shame a sociologist. Big Bang cosmology, he writes,

> owes its acceptance as a physical principle primarily to the uncritical and premature representation of [the redshift-distance relationship] as an empirical fact. . . . Observed discrepancies . . . have been resolved by a pyramid of exculpatory assumptions, which are inherently incapable of noncircular substantiation.

These are strong words of remonstration, but they are not implausible. Having constructed an elaborate scientific orthodoxy, cosmologists have acquired a vested interest in its defense. The astrophysicists J.G. Hoessell, J.E. Gunn, and T.X. Thuan, for example, report with satisfaction that within the structures described by G.O. Abell's *Catalog of Bright Cluster Galaxies* (1958), prediction and observation cohere perfectly to support Hubble's law. Abell's catalog is a standard astronomical resource, used by cosmologists everywhere—but it is useless as evidence for Hubble's law. "In determining whether a cluster meets selection criterion," Abell affirms, "it was assumed that their redshifts were proportional to their distance." If this is what Abell *assumed*, there is little point in asking what conclusions he *derived*.

The fact that the evidence in favor of Hubble's law may be biased does not mean that it is untrue; bias may suggest nothing more than a methodological flaw. But Segal is persuaded that when the evidence is soberly considered, it *does* contravene accepted doctrine, statistical sloppiness functioning, as it so often does, simply to conceal the facts.

A statistical inference is compelling only if the samples upon which it rests are objectively compelling. Objectivity, in turn, requires that the process of sampling be both reasonably complete and unbiased. Segal and his colleagues have taken pains to study samples that within the limits of observation are both. Their most recent study contains a detailed parallel analysis of Hubble's law across four wave bands, one that essentially surveys all stellar objects within each band. The analysis is based on new data drawn from the G. de Vaucoleurs survey of bright cluster galaxies, which includes more than 10,000 galaxies. Hubble's own analysis, it is worthwhile to recall, was limited to twenty galaxies.

The results of their analysis are disturbing. The linear relationship that Hubble saw, Segal and his collaborators cannot see and have not found. Rather, the relationship between redshift and flux or apparent brightness that they have studied in a

large number of complete samples satisfies a quadratic law, the redshift varying as the square of apparent brightness. "By normal standards of scientific due process," Segal writes, "the results of [Big Bang] cosmology are illusory."

Cosmologists have dismissed Segal's claims with a great snort of indignation. But the discrepancy from Big Bang cosmology that they reveal is hardly trivial. Like evolutionary biologists, cosmologists are often persuaded that they are in command of a structure intellectually powerful enough to accommodate gross discrepancies in the data. This is a dangerous and deluded attitude. Hubble's law embodies a general hypothesis of Big Bang cosmology—namely, that the universe is expanding—and while the law cannot be established by observation, observation *can* establish that it may be false. A statistically responsible body of contravening evidence has revealed something more than an incidental defect. Indifference to its implications amounts to a decision to place Big Bang cosmology beyond rational inquiry.

Monlam Chemno

WHATEVER THE facts may be, the Big Bang is also an event informed by the majesty of a great physical theory. Einstein published the equations for general relativity in 1915, and more than 80 years later, general relativity remains the only theoretical instrument remotely adequate to the representation of the universe as a whole.

General relativity is first and fundamentally an account of gravity, the force that pulls ballerinas to the ground and that fixes the planets in elliptical orbits around the sun. At the beginning of the scientific era, Isaac Newton described a universe in which space and time are absolute. The measured beating of a great clock is heard, and it is heard everywhere at once. Particles move within the unchanging vault of space. Material objects attract one another with a force proportional to their mass and inversely proportional to the square of the distance between them.

A metaphysical reorganization is required before Newton's caterpillar can emerge as Einstein's butterfly. The elements of general relativity are physical *processes*, a word signifying something that starts at one time and at one place and that ends at another time and another place, and so crawls along a continuum whose intrinsic structure has four dimensions. Within the arena of these physical processes, the solid structures of the Newtonian universe undergo a dissolution. The great vault of space and the uniformly beating heart dwindle and then disappear: *this* universe is one in which space and time have fused themselves into a single entity, and *its* heart is an ever-changing but reciprocating relationship between space-time and matter. Material objects direct the space and time that surround them to curve, much as a bowling ball deforms the mattress on which it rests; the curvature of space-time determines the path undertaken by physical processes, much as an ant crawling on that mattress must travel a curved path to get where it is going.

Newtonian gravity acts at a distance and as a force, the very bowels of the earth reaching to enfold an object and pull it down. But while Newton was able quantitatively to describe how gravity acts, he was unable to say why it acts at all, the aching attraction of matter for matter having no other explanation than the fact that it is so. General relativity provides an explanation of gravity in terms of the curvature of space and time. No forces are involved, and none is invoked, but gravity nonetheless emerges in this universe as a natural expression of the way the cosmos is constructed.

Freely moving objects, Einstein assumed, follow a path covering the shortest distance between points in space and time. Within the ambit of a large material object, the shortest distance between such points is curved. Ballerinas accelerate toward the center of the earth after being thrown upward by their partners because acceleration is required by the geometry in which they are embedded. In this fashion, gravity disappears as a force but remains as a fact.

If the analysis of gravity is at the center of general relativity, the intellectual tools responsible for its analysis—the equations that describe the ever-changing relationship between curvature and material objects—are responsible as well for its local character. For many years, the most precise and most interesting tests of the theory were conducted within the narrow confines of our own solar system. Cosmology, however, is a *global* study, one in which the universe itself is the object of contemplation, and not any of its parts. The conveyance from the local structure of the universe (the sun, the solar system) to the universe as a whole must be negotiated by a daring series of inferences.

In describing matter on a cosmic scale, cosmologists strip the stars and planets, the great galaxies and the bright bursting supernovae, of their uniqueness as places and things and replace them with an imaginary distribution: the matter of the universe is depicted as a great but uniform and homogeneous cloud covering the cosmos equitably

in all its secret places. Cosmologists make this assumption because they must. There is no way to deal with the universe object by object; the equations would be inscrutable, impossible to solve. But however useful the assumption of homogeneity may be mathematically, it is false in the straightforward sense that the distribution of matter in the universe is not homogeneous at all.

Having simplified the contents of the universe, the cosmologist must take care as well, and for the same reason, to strip from the matter that remains any suggestion of particularity or preference in place. The universe, he must assume, is isotropic. It has no center whatsoever, no place toward which things tend, and no special direction or axis of coordination. The thing looks much the same wherever it is observed.

The twin assumptions that the universe is homogeneous and isotropic are not ancillary but indispensable to the hypothesis of an expanding universe; without them, no conclusion can mathematically be forthcoming. Together, these two assumptions are like the figured bass needed to chant what in Tibetan is known as *Monlam Chemno*, the great prayer to the cosmos.

Specification in the Dark

AN EQUATION draws the noose of an identity between two or more items. The field equations of general relativity draw that noose between curvature (the metric structure of the universe) and matter (its stress-energy tensor). But it is one thing to specify an equation, and quite another to solve it.

The mathematician in him having taken command, Einstein endeavored in 1917 to provide cosmological solutions for the field equations of his own theory. He struggled with increasing vexation. The models he was able to derive indicated that the radius of the universe was either expanding or contracting; it was a conclusion that offended his aesthetic sensibilities. By adding a parameter to his equations—the so-called cosmological constant—he was in the end able to discover a static solution, one that revealed a universe finite in extent, but unbounded, like the surface of a sphere. This static solution has a habit of dropping from the view of cosmologists, who routinely aver that Einstein's theory of general relativity uniquely specifies an expanding universe. Not so.

Einstein had hoped that the equations of general relativity would determine a single world model, or cosmic blueprint. In this he was destined to be disappointed. Months after he discovered one solution of the field equations, Willem de Sitter discovered another. In de Sitter's universe, there is no matter whatsoever, the place looking rather like a dance hall in which the music can be heard but no dancers seen, radiation filling the empty spaces and ricocheting from one end of creation to another.

In the 1920's, both Aleksandr Friedmann and Georges Lemaître discovered the solutions to the field equations that have dominated cosmology ever since, their work coming to amalgamate itself into a single denomination as Friedmann-Lemaître (FL) cosmology. Gone from their models is the cosmological constant (although it is resurrected in various inflation scenarios), and as a result the universe breathes voluptuously, its radius expanding or contracting with time.

FL cosmology does not assign to the universe a unique geometrical identity, or specify its fate forever; general relativity is mathematically compatible with a number of different physical scenarios. Like the surface of a sphere, the universe may well be closed, the whole thing falling back on itself at the end of time. A certain symmetry prevails, the life of things and all the drama of creation caught between two singularities as the universe traces a trajectory in which its initial effervescent explosion is followed by a subsequent enervating contraction.

Or yet again, the universe may well be open, space and time forever gushing into the void but with ever-decreasing intensity, like an athlete panting in shallow breaths. Such a universe is purely a mathematician's world, one seen only by the exercise of certain obscure mental muscles, and regarded by physicists (and everyone else) with glum distaste.

Or, finally, the universe may be one that occupies the Euclidean space of high-school textbooks and intuition alike, balanced precariously but balanced forever on a knife's edge between expansion and contraction.

If its predictive capacities seem unstable, FL cosmology has other peculiarities as well. Whatever the specific form its solutions take, they are alike in assigning dynamic properties to the universe as a whole. The classical distinction between the eternal vault of space and time and its entirely perishable contents has disappeared. The universe in FL cosmology is *itself* bound to the wheel of being, with space and time no more permanent than water and air. Light blazes, the show commences, and like some magnificent but mysterious organism, the universe expands with an exuberant rush of energy and floods nothingness with the seeds of

being. In this fundamental respect, FL cosmology breaks both with tradition and with common sense.

At Time Zero

THE INTERPRETATION of a physical theory partakes of a dark art, one in which mathematical concepts are ceded dominion over the physical world. In practicing this art, the mathematician, like the necromancer that he is, is always liable to the temptation of confusing the structures over which he presides with things in the real world.

On the assumption—on the *assumption*—that the universe is expanding, it is irresistibly tempting to run time backward until the far-flung debris of the cosmos collects itself back into a smaller and smaller area. It seems evident, though, that this process of contraction and collapse may be continued only so far. An apple may be divided in halves, and then thirds, and then quarters, but even though the mathematical sequence of one half, one third, one fourth, and so on contains infinitely many terms, and converges ultimately to zero, the apple itself may be divided only finitely many times.

This straightforward point has been the source of grave confusion. "The universe," the astronomer Joseph Silk writes, "began at time zero in a state of infinite density." It is there that (by definition) a *singularity* may be found. "Of course," Silk adds, "the phrase 'a state of infinite density' is completely unacceptable as a physical description of the universe. . . . An infinitely dense universe [is] where the laws of physics, and even space and time, break down."

These are not words that inspire confidence. Does the phrase "a state of infinite density" describe a physical state of affairs or not? If it does, the description is uninformative by virtue of being "completely unacceptable." If it does not, the description is uninformative by virtue of being completely irrelevant. But if the description is either unacceptable or irrelevant, what reason is there to believe that the universe began in an initial singularity? Absent an initial singularity, what reason is there to believe that the universe began at all?

When prominent cosmologists tie themselves in knots, charity tends to assign the blame to the medium in which they are navigating—books for a general audience—rather than the message they are conveying. But when it comes to the singularities, the knots form in *every* medium, evidence that the message is at fault and not the other way around. Cosmologists often claim that the mathematicians among them have demonstrated what they themselves may be unable clearly to express. In a passage that is typical, the astrophysicist Kip Thorne writes that "[Stephen] Hawking and [Roger] Penrose in 1970 proved—without any idealizing assumptions—that our universe must have had a space-time singularity at the beginning of its Big Bang expansion." But while it is true that Hawking and Penrose proved something, what they demonstrated remains within the gerbil wheel of mathematics; any additional inference requires a connection that the mathematician is not in a position to provide.

The concept of a singularity belongs *essentially* to mathematics. Singularities are not experimentally accessible objects. They cannot be weighed, measured, assessed, replicated, balanced, or seen by any modality of the senses. Within certain mathematical contexts, the concept has real content. An ordinary curve goes up one side of the blackboard and down the other; it *changes* its direction at a singular point. There are singularities within the calculus, and singularities in complex function theory where imaginary numbers loiter, and singularities in the space of smooth maps. There are singularities within general relativity as well, but the term covers a variety of cases, and the singularities within general relativity are distinctly odd.

In most mathematical theories a natural distinction is drawn between a figure and its background: a curve arcs within the broader ambit of an enveloping space, a mapping is easily distinguished from the spaces it connects. Typically, it is the figure that admits of a singularity: the curve changes its direction or the mapping breaks down, while the background stays the same. But in general relativity, it is the *background* that suffers a singularity, the very fabric of space and time giving way with a rip as curvature zooms off to infinity and space and time contort themselves. For the purposes of describing such singularities, the usual mathematical techniques are unavailing.

That having been said, here is what Hawking and Penrose brought under the control of a mathematical demonstration. The setting is FL cosmology and *only* FL cosmology. There are three kinds of universe to consider, and innumerably many species within each type. Those that are open and forever gushing into the void are called hyperbolic. Within almost all of those hyperbolic universes, almost all processes begin at a point in the past. Within the two types of universe that remain, there is bound to be at least one process that has begun somewhere in the past.

Despite the tics—"almost all," "at least one"—the Penrose-Hawking theorems do indeed demon-

strate that some universes begin in an initial singularity. But the light thrown by the Penrose-Hawking theorems flickers over a mathematical theory and so a mathematical universe. The universe that we inhabit is a physical system. Nothing but grief can come of confusing the one for the other. FL cosmology requires the existence of space-time singularities, but there is nothing in the Penrose-Hawking theorems to suggest that a space-time singularity corresponds to an explosion, or marks the beginning of an expansion, or describes an accessible portion of space and time, or connects itself to any physical state of affairs whatsoever.

Mathematical concepts achieve physical significance only when the theories in which they are embedded are confirmed by experience. If a space-time singularity is not a physical event, no such confirmation can logically be forthcoming. With the argument rolled backward, it follows that if these mathematical theories are not confirmed by experience, then neither have they achieved any physical significance.

It is Einstein who expressed the most reasonable and deeply thought views on this matter. "One may not therefore assume the validity of the [field] equation for very high density of the field and of matter," he remarked, "and one may not conclude that the beginning of the expansion must mean a singularity in the mathematical sense. All we have to realize is that the equations may not be continued over such regions."

The sharp, clean, bracing light that the Big Bang was to have thrown on the very origins of space and time lapses when it is most needed. The relevant equations of general relativity fall silent at precisely the moment we most wish they would speak.

The Closing Circle

LIKE SO many haunting human stories, the scientific story of the Big Bang is circular in the progression of its ideas and circular thus in its deepest nature. Cosmologists have routinely assumed that the universe is expanding because they have been persuaded of FL cosmology; and they have been persuaded of FL cosmology because they have routinely assumed that the universe is expanding. The pattern would be intellectually convenient if it were intellectually compelling.

If the evidence in favor of Big Bang cosmology is more suspect than generally imagined, its defects are far stronger than generally credited. Whatever else it may be, the universe is a bright, noisy, energetic place. There are monstrously large galaxies in the skies and countlessly many suns burning with fierce thermonuclear fires. Black holes are said to loiter here and there, sucking in matter and light and releasing it slowly in the form of radiation. Whence the energy for the show, the place where accounts are settled? The principles of 19th-century physics require that, in one way or another, accounts *must* be settled. Energy is neither created nor destroyed.

Hot Big Bang cosmology appears to be in violation of the first law of thermodynamics. The global energy needed to run the universe has come from nowhere, and to nowhere it apparently goes as the universe loses energy by cooling itself.

This contravention of thermodynamics expresses, in physical form, a general philosophical anxiety. Having brought space and time into existence, along with everything else, the Big Bang itself remains outside any causal scheme. The creation of the universe remains unexplained by any force, field, power, potency, influence, or instrumentality known to physics—or to man. The whole vast imposing structure organizes itself from absolutely nothing.

This is not simply difficult to grasp. It is incomprehensible.

Physicists, no less than anyone else, are uneasy with the idea that the universe simply popped into existence, with space and time "suddenly switching themselves on." The image of a light switch comes from Paul Davies, who uses it to express a miracle without quite recognizing that it embodies a contradiction. A universe that has *suddenly* switched itself on has accomplished something within time; and yet the Big Bang is supposed to have brought space and time into existence.

Having entered a dark logical defile, physicists often find it difficult to withdraw. Thus, Alan Guth writes in pleased astonishment that the universe really did arise from "essentially . . . nothing at all": as it happens, a false vacuum patch "10^{-26} centimeters in diameter" and "10^{-32} solar masses." It would appear, then, that "essentially nothing" has both spatial extension and mass. While these facts may strike Guth as inconspicuous, others may suspect that nothingness, like death, is not a matter that admits of degrees.

The attempt to discover some primordial stuff that can be described both as nothing and as something recalls the Maori contemplating the manifold mysteries of *po*. This apparently gives Stephen Hawking pause. "To ask what happened before the universe began," he has written, "is like asking for a point on the Earth at 91 degrees north latitude." We are on the inside of the great sphere of space and

time, and while we can see to the boundaries, there is nothing beyond to see if only because there is nothing beyond. "Instead of talking about the universe being created, and maybe coming to an end," Hawking writes, "one should just say: the universe is."

Now this is a conclusion to which mystics have always given their assent; but having concluded that the universe just "is," cosmologists, one might think, would wish to know *why* it is. The question that Hawking wishes to evade disappears as a question in physics only to reappear as a question in philosophy; we find ourselves traveling in all the old familiar circles.

Contract

STANDING AT the gate of modern time, Isaac Newton forged the curious social pact by which rational men and women have lived ever since. The description of the physical world would be vouchsafed to a particular institution, that of mathematical physics; and it was to the physicists and not the priests, soothsayers, poets, politicians, novelists, generals, mystics, artists, astrologers, warlocks, wizards, or enchanters that society would look for judgments about the nature of the physical world. If knowledge is power, the physicists have, by this arrangement, been given an enormous privilege. But a social arrangement is among other things a contract: something is given, but something is expected as well. In exchange for their privilege, the physicists were to provide an account of the physical world at once penetrating, general, persuasive, and true.

Until recently, the great physicists have been scrupulous about honoring the terms of their contract. They have attempted with dignity to respect the distinction between what is known and what is not. Even quantum electrodynamics, the most successful theory ever devised, was described honestly by its founder, Richard Feynman, as resting on a number of unwholesome mathematical tricks.

This scrupulousness has lately been compromised. The result has been the calculated or careless erasure of the line separating disciplined physical inquiry from speculative metaphysics. Contemporary cosmologists feel free to say anything that pops into their heads. Unhappy examples are everywhere: absurd schemes to model time on the basis of the complex numbers, as in Stephen Hawking's *A Brief History of Time*; bizarre and ugly contraptions for cosmic inflation; universes multiplying beyond the reach of observation; white holes, black holes, worm holes, and naked singularities; theories of every stripe and variety, all of them uncorrected by any criticism beyond the trivial.

The physicists carry on endlessly because they can. Just recently, for example, Lee Smolin, a cosmologist at the University of Pennsylvania, has offered a Darwinian interpretation of cosmology, a theory of "cosmological natural selection." On Smolin's view, the Big Bang happened within a black hole; new universes are bubbling up all the time, each emerging from its own black hole and each provided with its own set of physical laws, so that the very concept of a law of nature is shown to be a part of the mutability of things.

There is, needless to say, no evidence whatsoever in favor of this preposterous theory. The universes that are bubbling up are unobservable. So, too, are the universes that have bubbled up and those that will bubble up in the future. Smolin's theories cannot be confirmed by experience. Or by anything else. What law of nature could reveal that the laws of nature are contingent? Yet the fact that when Smolin's theory is self-applied it self-destructs has not prevented physicists like Alan Guth, Roger Penrose, and Martin Rees from circumspectly applauding the effort nonetheless.

A scientific crisis has historically been the excuse to which scientists have appealed for the exculpation of damaged doctrines. Smolin is no exception. "We are living," he writes, "through a period of scientific crisis." Ordinary men and women may well scruple at the idea that cosmology is in crisis because cosmologists, deep down, have run out of interesting things to say, but in his general suspicions Smolin is no doubt correct. What we are discovering is that many areas of the universe are apparently protected from our scrutiny, like sensitive files sealed from view by powerful encryption codes. However painful, the discovery should hardly be unexpected. Beyond every act of understanding, there is an abyss.

Like Darwin's theory of evolution, Big Bang cosmology has undergone that curious social process in which a scientific theory is promoted to a secular myth. The two theories serve as points of certainty in an intellectual culture that is otherwise disposed to give the benefit of the doubt to doubt itself. It is within the mirror of these myths that we have come to see ourselves. But if the promotion of theory into myth satisfies one human agenda, it violates another. Myths are quite typically false, and science is concerned with truth. Human beings, it would seem, may make scientific theories or they may make myths, but with respect to the same aspects of experience, they cannot quite do both.