A MODERN LOOK AT THE ORIGIN OF THE UNIVERSE

by Sten F. Odenwald

Abstract. In what follows, I review the modern theory of the origin of the universe as astronomers and physicists are coming to understand it during the last decades of the twentieth century. An unexpected discovery of this study is that the story of "cosmogenesis" cannot be completely told unless we understand the fundamental nature of matter, space, and time. In the context of modern cosmology space has become not only the bedrock (so to speak) of our physical existence, it may yield a fuller understanding of the universe itself.

Keywords: cosmology; Big Bang theory; quantum gravity; supersymmetry; geometrization of matter; multi-dimensional space; origin of universe

> The evolution of the world may be compared to a display of fireworks that has just ended: some few wisps, ashes and smoke. Standing on a cooled cinder, we see the slow fading of the suns, and we try to recall the vanished brilliance of the origin of the worlds.
>
> —G. Lemaitre

Even though hundreds of civilizations have appeared on this planet over the millennia, it is remarkable that only a few archetypes for the story of creation have emerged (James 1969). Of particular interest are the many attempts at describing conditions just before the origin of the physical world (Long 1963; Brandon 1963). Since the time these creation stories were conceived, our understanding of the

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physical world has grown and matured, to the point where modern definitions of space, time, and matter are far more sublime than our ancestors could have imagined.

THE BIG BANG

The basis of the modern history of the evolution of the universe is Albert Einstein's 1915 theory of general relativity, the first theory to establish the equivalence between gravitational fields and the mathematical properties of space—in particular, its curvature. When Einstein in 1917 applied his theory to the dynamics of the universe, he discovered that Newton's static, infinite universe was unstable and would collapse. Since at that time no observation suggested the universe was undergoing collapse, Einstein added an *antigravity* term to his equations in the guise of a quantity called the *cosmological constant*. As he expected, this addition resulted in a static, infinite, eternal universe in keeping with the preconceptions of that era. Since so little was known about the universe, this constant could not be dismissed out of hand on observational grounds. This also led to the mathematical investigations by the Belgian Catholic priest Georges Lemaitre (1933) and, earlier, to the "empty" cosmological models by Willem de Sitter (1916).

In 1922, soon after Einstein proposed his static model for the universe, Alexander Friedmann found that this was only one of a much larger family of cosmological models that did not have a cosmological constant term. Three solutions to the equation were possible under these conditions: two described universes that evolved from a single origin in time and expanded indefinitely as infinite universes; the third also described a universe that began at a fixed time, but its initial expansion was followed by a collapse. Before he died (in 1924) Friedmann had also demonstrated that randomly placed observers within these universes would all see objects in space moving away from them at the same rate, but with their velocity proportional to the distance between them. This "law of recession" was confirmed between 1927 and 1931 by Edwin Hubble, during a study of distant galaxies (Weinberg 1977b). Since then there has been little doubt that Friedmann's cosmologies are the correct models for the evolution of the universe.

The mathematical meaning behind the Friedmann cosmologies is quite clear but difficult to grasp intuitively. We are, of course, familiar with ordinary explosions in which matter is thrown from a center and expands. The essential intuitive difficulty with the "explosion" of the universe, described in general relativistic cosmology, is that both space and time are created, along with matter, at "time zero." This instant is termed *the singularity* since physical quantities (such as density) become infinite as the volume of space occupied by matter vanishes. The circumstances of this simultaneuous coming into existence of space, time, and matter have been the topic of hundreds of articles and books over the years. Until recently, the earliest moments in the unfolding of our universe have resisted logical analysis in all but the most rudimentary terms. Major advances have come about not by concentrating exclusively on the grand design of the universe, but by focusing on the innermost construction of matter and the laws that regulate its motion. Paradoxically, it seems that only by understanding the rules governing matter and space at the subatomic level have we been able to describe the first few moments in the history of the universe.

A JOURNEY BACK THROUGH TIME

Although general relativity can tell us about the evolution of spacetime,[1] it does not explain the material structure that emerges from the singularity. Only by the addition of a theory of matter can these models be fleshed out with the essential ingredients of physical existence: atoms, stars, and galaxies (see Schramm 1983).

The characteristic of matter that has considerable bearing on our understanding of creation is its compositeness and how this changes with temperature. At low temperatures, microscopic but complex molecules, such as DNA, and gigantic but simple objects, such as planets, can exist as stable forms. At sustained temperatures above 10,000° K, planets evaporate and compounds and molecules dissociate into atoms. Above 100,000° K, atoms are stripped of their electrons (a process called ionization), leaving a hot, charged gas of free atomic nuclei and electrons as the most complex forms of matter. Although electrons are not known to be composite, atomic nuclei, with their tightly bound protons and neutrons, are composite structures. Above temperatures of 10 billion degrees, however, all atomic nuclei dissolve into their constituent protons and neutrons, and matter loses its recognizable characteristics. The 108 elements in the periodic table vanish at these temperatures, leaving a hot gas of electrons, protons, and neutrons. But even this unimaginably extreme state is not the most elementary state of matter, for we know that protons and neutrons are themselves composite particles, each consisting of three quarks (Glashow 1975). At 1,000 trillion degrees, we expect that protons and neutrons will dissolve into their constituent quarks, which, like the ever-present electrons, are what most

Fig. 1. The Known Fundamental Particles of the Physical World

Fermions (Matter Particles)		Bosons (Force Carriers)		
Leptons	Quarks	Scalar	Vector	Tensor
electron	Up	Higgs	photon	graviton
muon	Down			
tauon	Strange		gluons	
electron neutrino	Charmed			
muon neutrino	Top		W^+ W^- Z°	
tauon neutrino	Bottom			

physicists consider to be fundamental particles (Harari 1983). Depending on which model one trusts at still higher energies, this quark-electron gas becomes hotter, but no new "subquark" particles emerge.

Considering the attributes of matter at ever-increasing temperatures, we note a simplification. At sufficiently high temperatures, billions of distinct chemical compounds possible at low temperatures are replaced by the twelve leptons and quarks shown in figure 1. This is not merely an a priori, reductionist assumption about the world, but an objective, hard-won fact of our existence. Therefore, to the extent that all modern theories of cosmology state that our universe emerged from a condition of high density and temperature (Gamow 1948; Turner and Schramm 1979) in what Gamow termed the Big Bang, that universe must have consisted of much simpler matter than the universe we now experience. The description of the universe after the Big Bang, in particular its contents, becomes ever more simple the closer (in time) we approach its origin. Today's world still contains this simplicity, but it is hidden in the subtle symmetries that regulate the inner workings of the physical world. We can glimpse these symmetries in action by performing experiments with "atom smashers" and similar devices. We also can find evidence for them in our mathematical descriptions of matter.

At what time were these high-temperature conditions common? The mathematical statement of the Big Bang model says that the temperature of matter and radiation in space are related to the elapsed time since the Big Bang, according to the prescription $T = 10$ billion degrees K / $\sqrt{t}$, with time (t) measured in seconds after the Big Bang. Beginning with the temperature of the present world at about 3° K some 15 to 20 billions years after the Big Bang (ABB), it has been calculated that matter was completely ionized by about 700,000 years

ABB. At three minutes ABB, the temperature reached about 1 billion degrees K and atomic nuclei began to dissolve. At 1 second ABB, only protons, neutrons, and electrons were present as well as the ever present fireball light from the Big Bang. Finally, at about 1 microsecond ABB, there was only a hot gas, consisting of quarks and leptons. The details of this generally accepted standard model, describing evolving conditions in the early history of the universe, are provided by interrogating widely used and accepted models of nuclear physics.

To look beyond this almost unthinkably early moment of 1 microsecond ABB requires us to seek an even deeper level to our understanding of the physical world—an understanding not just of the building blocks of matter, but of the forces through which they interact.

THE SEARCH FOR SYMMETRY AND GRAND UNIFICATION

Tremendous progress has been made during the last 50 years toward understanding the forces and fundamental particles of our world in terms of an all-encompassing mathematical theory (Weinberg 1977a). Progress toward realizing this comprehensive worldview has been slow, however, since the fundamental forces in nature bear little resemblance to one another, either in their range, strength, or effects (Quigg, 1985). The way in which leptons and quarks combine to create the familiar structures in our world are determined by a quartet of forces: gravity, electromagnetism, and strong and weak nuclear forces. The strong force, mediated by a family of eight particles called gluons, binds quarks together into protons and neutrons, and holds them together inside the nuclei of atoms. The weak nuclear force produced by the exchange of what are called W^+, W^-, and Z° bosons (Watkins 1986) causes the spontaneous, random decay of some subnuclear particles into more stable by-products. The electromagnetic force, mediated by massless photons that travel at the speed of light, causes the repulsion and attraction of charged particles, and electrons to be bound into atoms, thereby making stable, neutral atoms and molecules that can partake in chemical reactions. Finally gravity, which is, paradoxically, the weakest and most far reaching of the four, is the controlling force for pulling vast assemblages of matter into planets, stars, and galaxies. These forces span a wide range of influence, from the most distant scrap of stellar matter in the universe to the heart of nuclear matter.

Since Michael Faraday's invention of the concept of the electro magnetic field[2] and James Clerk Maxwell's mathematical development of field theory during the 1860s, the world of the physicist has increasingly become the one described by Steven Weinberg (in Pagels 1985): "The essential reality is a set of fields . . . all else can be derived as a consequence of the quantum dynamics of those fields." Beyond the recognition that nature may be described as a pattern of interacting fields is the discovery that the many fields needed to build matter can be reduced to a hierarchy of progressive simplification.

By the end of the 1960s, for example, Sheldon Glashow, Steven Weinberg, and Abdus Salam (1968) had formulated a quantum field theory[3] that combined electromagnetic and weak forces into a mathematical framework, called the electroweak theory. This was soon followed (in the 1970s) by a theory for the strong force, called quantum chromo dynamics (QCD). During this time there was also a growth of interest in combining the QCD and electroweak theories into a grand unification theory (GUT) that would unify all three interactions (Georgi and Glashow 1974; Georgi 1981). This unification of seemingly incompatible forces can be described as the consequence of symmetries that the equations describing the forces share. The types of mathematical symmetries that are allowed have been classified in a branch of mathematics called group theory; however, many of the most promising types of symmetries did not provide the correct starting points for correct theories of matter. Simple explanations for many unresolved questions about particle types, masses, and interactions were either lacking or gave incorrect predictions. For example, why are there three generations of progressively more massive quarks and leptons? Where does the gravitational force enter the theory? One of the surprising features of nearly all GUTs is that they predict that matter itself is inherently unstable. After 10^{32} to 10^{34} years, even an eternally expanding universe may consist of only a dilute gas of electrons, neutrinos, and photons once all of the more familiar forms of matter disintegrate. Matter is but a fleeting phase in an eternal universe.

Soon after the pursuit of GUTs began in earnest in the mid-'70s, a major discovery was independently made by two groups of theoreticians: Freedman, von Nieuwenhuizen, and Ferrara (1976), and Deser and Zumino (1976). Their work demonstrated that it is possible to create a mathematical formalism showing how the particles producing matter (quarks and leptons) are related to particles that mediate the forces (gluons, photons, etc.). This mathematical relationship was so startling and comprehensive that it was termed a supersymmetry. Almost miraculously, equations describing supersymmetry included gravity as an absolutely vital coingredient.

What had been sought was a method for treating all the fundamental particles in a common language. Supersymmetry made it possible to mathematically transform quarks into photons; however, to make this supersymmetry transformation work properly in our physical world, the theory predicted that a new field would have to be introduced whose characteristics match those of gravity. A theory originally developed to describe three forces (electromagnetism and the strong and weak nuclear forces) had managed to bootstrap into existence a description for the fourth force as well: gravity.

In spite, of initial success the supersymmetry theory (Freedman and von Nieuwenhuizen 1978) suffered from inconsistencies that could not be easily remedied. For example, some variants of supersymmetry theory predicted fewer fundamental particles in nature than those already known. These difficulties have apparently been overcome by the theoretical work of Michael Green and John Schwartz (1984), who developed a theory called *superstrings*. It was patterned after an older theory of matter in vogue during the early '60s, but the conceptually simpler quark model outmoded the older theory, so that the latter was regarded as a mathematical curiosity and was not pursued in mainstream physics.

In superstring theory, all particles are represented mathematically as one-dimensional objects called *strings* that exist in a ten-dimensional spacetime. Oscillations of these strings account for a rich collection of particles whose lightest members have no mass (e.g., photons, gluons and gravitons) and whose next lightest members weigh 10^{17} GeV or more![4] All the familiar particles in our world are on the lowest rung of an infinitely high ladder of oscillatory modes of these string particles. Depending on the topology and symmetry of the underlying, ten-dimensional spacetime, the motion of the strings corresponds to particles with different properties (Green 1986).

The idea that unification could be achieved by considering spacetime to have more than the customary four dimensions (the count is now three dimensions for space and one for time) is not new. Theodore Kaluza and Oskar Klein (1926) proposed in the 1920s that gravity and electromagnetism could be combined into one mathematical framework by extending Einstein's general theory of relativity into the 5th dimension. This extra dimension (four for space and one for time) was physically different from the other three spatial dimensions in that it was of finite length, 10^{-33} cm, or much smaller than even the diameter (10^{-14} cm) of an atomic nucleus (Freedman and von Nieuwenhuizen 1985; Odenwald 1984). However, though imperceptible to humans, subatomic particles and quantum fields derive their special characteristics from their "motion" through these additional dimensions.

THE GEOMETRIZATION OF MATTER

Apart from the search for a unified particle theory that included gravity as a natural ingredient, a separate line of investigation had been pursued by theoreticians schooled primarily in general relativity and topology. Rather than beginning with the messy search for electronuclear unification and inferring how best to incorporate gravity as a quantum field, this parallel approach starts with a direct mathematical study of what the basic postulates of quantum gravity theory include. The central idea is almost deceptively simple: If we were to follow a line on the "fabric" of three-dimensional space, where would the points on that line cease to be space and become the embedded quark or lepton? Since W.K. Clifford presented his 1879 paper, "On the Space Theory of Matter," and Einstein gave substance to this line of inquiry by his theory of general relativity in 1915, much has gone into formulating a theory of "quantum gravity" (DeWitt 1983) in which matter is treated in geometric terms. Einstein (1950) was so convinced of the correctness of this approach that he wrote: "The material particle has no place as a fundamental concept in field theory. Even Maxwell's electrodynamics are not complete for this reason. Gravity as a field theory must also deny a preferred status to matter" (Einstein 1950, 14).

A more radical notion which emerged during the turbulent sixties is voiced by John Wheeler (Misner, Thorne and Wheeler 1973, 1202): "What else is there out of which to build a particle except geometry (spacetime) itself?" Wheeler proposed that what we normally think of as an electric charge is merely electric "lines of force" that have become trapped in the contorted, knotty topology of spacetime. Spacetime at a scale of 10^{-33} cm was imagined not as a smooth, flat sheet of paper, but as a shape in which loops and bridges between one region in space and another appeared and vanished. The geometry of space at these scales was highly curved and warped, subject to energetic, random fluctuations in its shape. It can even be said that at this level, space cannot make up its mind which of an infinite number of topological possibilities it would like to manifest. Wheeler became an outspoken proponent of this "foam-like structure to spacetime" viewpoint, developing in 1964 a "superspace formalism" to describe the quantum evolution of spacetime into its present large-scale geometry. Spacetime, therefore, is not a static stage upon which nature dances, but it reverberates between a multitude of alternate geometries. In a curious form of cosmic democracy, the spacetime we inhabit is a superposition of an infinitude of alternate possibilities for its geometry. Their combination, each according to its likelihood, results in our observed spacetime geometry. At the Planck scale of 10^{-33} cm, however, spacetime has an indeterminate geometry. and fluctuates between all of its many possibilities. Like the interfering ripples on a pond, our universe may represent the confluence of many possible alternatives that imperceptably flash in and out of existence.

Other theoreticians (such as Roger Penrose [1975]) adopted even more radical viewpoints, suggesting that spacetime is not a primary concept but is built of even more elementary objects, called Robertson congruences—or, more simply, twistors. Collective interactions between twistors knit four-dimensional spacetime together much as a three-dimensional garment is fashioned from one-dimensional thread. Recently the mathematical connections between superstring theory and twistors have been discovered (Hughton 1986) so that again one finds apparently independeant avenues of thinking leading to mutually self-consistent descriptions for the deep structure of spacetime. Spacetime is not fundamental, but synthetic. It is not static, but dynamic. Whether any of these ideas will be elevated to a Theory of Everything, or at least become a feature of such a theory, is an open question. However, we need not wait for some ultimate theory of matter before we may begin to apply these ideas to the origin of the universe.

It is difficult to comprehend what such descriptions for space and the universe might entail. What little we glean of the principles of quantum gravity theory and its physical implications seems to leave us with few solid islands on which we can stand. Our familiar, intuitive notions about space and time, "before" and "after," may be irrelevant once these deterministic or causal relationships are replaced by the shifting probabilities of the quantum world. It is worth reemphasizing that of paramount importance in the description of our universe's origins is the accuracy of our understanding of space. Space is not, apparently, a material medium although it can exert itself in such a manner under appropriate conditions; it is not "nothing" in the colloquial sense, since it may well have a complex topology, extending into higher dimensions, that dictates the characteristics of matter. Having reduced our familiar world to an interplay of quarks and leptons, and then into a patina of interacting quantum fields and resonating spacetime, cosmologists schooled in quantum physics have used these ideas to describe the earliest events in the unfolding of the universe.

THE "INFLATIONARY" UNIVERSE

Beginning at 1 microsecond ABB, four distinct forces are in evidence amid a hot soup of quarks and leptons. As we move further back in time, the average energy of each particle climbs to 200 GeV by about 10^{-15} seconds ABB. The individuality of the electromagnetic and weak forces begins to blur, and they are soon indistinguishable. Although we can still distinguish quarks from leptons, both begin to lose the attribute we call mass. Because leptons do not possess the appropriate "color" charge that characterizes quarks, the quarks continue to feel the strong force whereas the leptons do not. Once the particle energies exceed about 10^{15} GeV, corresponding to a time 10^{-35} seconds ABB, we enter an even stranger world. Gluons carrying the strong force, now resemble the quanta carrying the electroweak force, which gradually undermines the distinction between these two forces. Eventually, a single "electronuclear" force emerges and with the ever present force of gravity, becomes the only distinct way in which matter may interact with itself.

The rate of expansion of the universe is not immune from the changing pressures exerted by the particles and fields that its spacetime encompasses. For example, particles called Higgs bosons do much more than merely break the symmetry between strong and electroweak forces as the universe cools and expands. When incorporated into Einstein's general relativity equations, these yet-to-be-discovered particles produce an antigravity effect, just as Einstein's cosmological constant was intended to. The result is an enormous expansion of the universe. This phenomenon, first proposed by Alan Guth (1981), Linde (1982a), and Albrecht and Steinhardt (1982), is called *inflation* and appears to be a cosmological consequence of nearly all known GUTs.

The essential feature of inflationary cosmological models is that soon after the universe cooled below the GUT transition energy of about 10^{15} GeV at 10^{-35} seconds ABB, it entered a phase of rapid expansion due to the behavior of one or more of the fields[5] in the grand unification scheme. During this brief phase, the separation between neighboring points in space increases exponentially, by a trillion-trillion times or more. Without inflation, cosmologists who attempt to understand the current size and uniformity of the universe are left with a variety of loose ends that can be eliminated only by a fine-tuning of initial conditions at the time of the Big Bang (Guth and Steinhardt 1984; Odenwald 1983).

GUT theories say that inflation ended when the universe became about 10^{-34} seconds old, although the precise duration of this inflationary phase is debated, depending on the grand unification theory that is used as the basis of calculation. This era is not the earliest one we can attempt to explore, but to understand what may have preceded it, we need to draw heavily on the concepts provided by quantum gravity theory: a theory still in its early stages of mathematical and conceptual development (DeWitt 1983; Odenwald 1987).

COSMOGENITUM EX NIHILUM

The reason that there is Something instead of Nothing is that Nothing is unstable (Frank Wilczyk, in Trefil 1983, 206).

As we apply the patchwork of theories we loosely term quantum gravity to our cosmological models, basic clues about the history of the universe earlier then 10^{-35} seconds ABB emerge. We begin to perceive the dim outlines of a time when all forces merge with gravity, and the final geometrization of matter becomes more than just a mathematical exercise. For many decades the "origin" question was lost in the violence of the singularity state predicted by Big Bang cosmology. Cosmologists, attempting to understand this period, were regularly confronted by the inadequacy of their mathematics. But recently new theoretical scaffolds have been erected, allowing us to speak more meaningfully about even this incomprehensible state that marks not only the birth of matter but of space and time as well. Actually, it was recognized rather early that the singularity state was an artifact of a theory, general relativity, that was pushed into a domain in which it could not be expected to make meaningful predictions. By a simple application of quantum mechanical principles, it is estimated that, at scales of 10^{-33} cm and durations shorter than 10^{-43} seconds,[6] general relativity will probably have to be supplanted by a theory that correctly handles the quantum aspect of the physical world. Consequently, the singularity condition would be replaced by a quantum condition far less extreme than infinite density, zero time, and zero spatial volume.

James Hartle and Stephen Hawking (1983), using a proto-quantum gravity theory, have demonstrated that just as quantum particles such as electrons may be described by the principles of quantum mechanics, the universe can be described in the same way. They showed that the singularity condition predicted by ordinary general relativity becomes smoothed out due to quantum interference. Instead of the universe emerging from a condition of vanishing space and time, which leads to the singularity state, the quantum fluctuations in the geometry of space prevented this. As for the origin of the universe, recent investigations provide many possibilities.

It was Edward Tryon (1973) who first proposed that since, as a whole, the total rest mass energy of the stars and galaxies in our universe, $E = mc^2$, is equal in magnitude to its gravitational energy, the total energy of the universe, which is expressed as the difference between these two, is zero. With this assumption, Heisenberg's uncertainty principle predicts that as a quantum fluctuation of the vacuum state, our universe of zero total energy could exist for eternity. In other words, characteristics of our universe would be analogous to those ghostlike quantum particles that flash in and out of existence within the atom and disturb electronic energy levels. For instance, the total charge of the universe would be exactly zero, as would its total angular momentum. Our universe resembles a "quantum fluctuation" in the energy of the physical vacuum that has lasted billions of years—not the billionths of a second that such fluctuations normally last! We have been describing nothing less than the creation of our entire universe (and beyond) out of the "empty" vacuum—a small patch of space, perhaps 10^{-33} cm across, that suddenly inflated to enormous size.

A persistent, intuitive feature of quantum gravity has been that, at small scales, the geometry of spacetime is ill defined and subject to random contortions, to changes of space curvature, and to interlinkages. Because general relativity posits that spacetime curvature is associated with a certain quantity of energy, and because energy and mass are interchangeable in the sense that $E = mc^2$, spacetime curvature can spontaneously produce matter under certain conditions (Hawking 1977; Ford 1987). The production of matter from rapidly changing spacetime fluctuations was introduced as a possibility by Sakharov (1968) and independently by Parker (1968).

Brout, Englert, and Gunzig (1978) carried Tryon's idea further by adding detail to this basic model. In their article "The Creation of the Universe as a Quantum Phenomenon" they showed how matter could be created out of the rapidly varying geometry of space, which then acted back on itself to create additional matter. In a cooperative process, the universe expanded in an inflationary state that ended once the spacetime irregularities had sufficiently smoothed themselves out. As Tryon remarked, "our universe is simply one of those things which happen from time to time" (1973, 1397).

Although Tryon's proposal was intriguing, it was treated as a curiosity when it first appeared. Atkatz and Pagels (1978) pointed out, some years later, that the concept of total energy is not rigorously definable in highly curved spacetimes and, therefore, Tryon's idea was incorrect, since at its earliest moments spacetime was in a highly curved state and not flat at all. Rather than the universe starting from a flat, empty spacetime, the preexisting state may have had some topological structure, as well as nonzero total energy, by virtue of its curvature. Taking into account the descriptions offered by superstring theorists, which suggest that spacetime may exist in ten or possibly twenty-six dimensions, Atkatz and Pagels proposed that the precreation phase may have had a ten-dimensional, closed geometry, out of which our familiar four-dimensional world spontaneously grew. The birth of our universe, like the formation of ice from cold water, was a phase transition, involving not just a change in particle attributes or forces, but possibly a sudden change in the very dimensionality and topology of spacetime as well (Scherk and Schwartz 1975; Englert 1982; Chodos and Detweiler 1980).

To some theoreticians, however, even these versions of the origin of our universe are too cluttered with loose ends. Alex Vilenkin suggested in an article in 1982 that rather than the preexisting state being a flat spacetime, or even a closed multidimensional one, this earliest conceivable state may have been quite literally nothing. Vilenkin imagined a nothingness that was the complete negation of all imaginable attributes that we might attach to the fields within spacetime or even to spacetime itself. It represented a state containing no fields, time, or space. It did not exist at any instant in time, nor was it located in space as we know it mathematically. The concept of dimensionality was irrelevant, and without time. Nothingness was the ultimate state of nonexistence. As Heinz Pagels (1986) explains, "The nothingness 'before' the creation of the universe is the most complete void that we can imagine—no space, time or matter existed. It is a world without place, without duration or eternity, without number. . . . Yet this unthinkable void converts itself into the plenum of existence—a necessary consequence of physical laws. Where are these laws written into the void? It would seem that even the void is subject to law, a logic that existed prior to time and space" (347).

The philosophical advantage of this state is that logically, since everything of physical significance was negated, one may not inquire where that negated state arose. To do so would imply that either a favored place or time existed prior to the universe's coming into being, and neither concept would have had a prior meaning. All further talk of "first moments" or "initial causes" would be halted once and for all. Since the human way of thinking refuses to accept barriers to seemingly rational questions, such as "What happened before that?" Vilenkin's scenario has not been the final word.

SELF-CREATED UNIVERSE

Clearly, that which we casually overlook and refer to as empty space is far more complex and sublime than has been naively assumed for millennia. Its proper understanding may well hold the key to the secrets of our existence and the very meaning of reality. Also, there may be a much broader context to creation than we can surmise by examining the finite region bounded by our observable universe.

Vilenkin's nihilistic interpretation of the cosmological equations is not the only defensible viewpoint in formulating a mathematical theory for the origion of the universe. A different scenario is represented by Sato et al. (1982), Sato and Kodama (1986), Linde (1983, 1987a), and Gunzig et al. (1987). The common feature of their models is that spacetime is an inherently unstable plenum. Much as a pencil balanced on its tip will fall with the slightest disturbance, Sato and his colleagues proposed that spacetime is capable of spontaneously ballooning into independent "child" universes. Gunzig speculates, on the basis of his mathematical investigation, that the more uniform and flat the precosmic spacetime, the greater the likelihood that it would have been unstable to such spontaneous curvature fluctuations. In time, as our universe grows more uniform and geometrically flat, it too may become the "mother spacetime" for an instability leading to the creation of a new universe! Once born, this "child" universe will become completely disconnected from ours, leaving no direct spatial or physical connection through which explorers may pass. By the remarkable process of quantum fluctuation, universes may therefore be self-creating and eternal. Moreover, this process may have occurred many times.

Soon after announcement of the inflationary cosmological model in 1981, Andrei Linde (1983) proposed an intriguing generalization. There may be a single spacetime, that not only transcends the portion within which our universe exists but includes an infinite number of other universes as well. If the concepts of quantum cosmology are correct, our universe emerged from a patch of this primordial spacetime, 10^{-33} cm across, at a time we associate with 10^{-43} seconds ABB. But this primordial spacetime, which we may call the *Ur-manifold*, contained many such patches, each destined to evolve according to its own set of randomly selected natural laws. Rather than search for a unification theory that leads only to the particles and forces in our universe, Linde proposed that, in some larger sense, all self-consistent unification theories may describe physical conditions in some other universe. As a consequence, in some of these patches the inflation era may have occurred, leading to many "big" universes, of which we are just one possibility. Some of the "failed" universes may have lived only a microsecond, or a few million years, before disappearing into the quantum foam of spacetime. Universes may exist that have gravity and electromagnetic forces, but perhaps no strong nuclear forces. Each inflated domain would be vastly larger than the region within it that any observer may perceive, and would appear very uniform within these locally observable regions. However, on the largest scales, these domains are part of a complex tapestry in spacetime whose segments may be interconnected by tunnels or "wormholes." For some domains, the tunnels may have evaporated, rendering these universes utterly disconnected. According to Linde (1987b), "It seems more likely that the universe is an eternally existing, self-producing entity, that is divided into many mini-universes much larger than our observable portion, and that the laws of physics, and even the dimensionality of spacetime, may be different in each [of them]."

Blau, Guendelman, and Guth (1987) suggest that quantum spacetime foam may be constantly creating bubble universes that derive from our spacetime. Some may evolve into universes such as our own. Since their expansion occurs in a region of spacetime completely disconnected from ours, they are forever beyond observation. Guth has even proposed that such bubble universes may be manufactured under laboratory conditions. The prescription for creating a universe like ours would require a "seed mass" of about 10 kg, converted into pure energy, within a region of space near the quantum gravity limit of about 10^{-33} cm. An aneurysm would then appear in our spacetime that would transform itself into such a universe. The connection between this nascent universe and ours would appear as a mini-black hole that would quickly evaporate, leaving not a trace of the event that had just occurred. Unfortunately, in an article titled "An Obstacle to Creating an Universe in the Laboratory" by Farhi and Guth (1987), the authors' calculations seemed to indicate that these conditions may not be easily achievable in practice, no matter how technologically advanced we become.

VISIONS OF THE FUTURE: A PERSONAL VIEW

> From our home on earth we look out into the distances and strive to imagine the sort of world into which we are born. . . . But with increasing distance, our knowledge fades . . . until at the last dim horizon we search among ghostly errors of observations for landmarks scarcely more substantial. (Edwin Hubble, in Pagels 1985, 81).

The precosmic void of our ancient forebear has now been filled by resonating spacetime and by quantum fields that silently come and go, without leaving a trace. As an astronomer, I am captivated by the new cosmologies that are emerging from the fertile ground of theoretical research. At the very least, we seem to have rational, logical explanations for much of the physical world, extending to the innermost constituents of matter and to within a microsecond or less of the Big Bang. This achievement must rank among the most significant intellectual accomplishments of the human race, yet, in terms of answering our age-old question, Where did the universe come from? it seems that we are no nearer an ultimate, simple answer—if one indeed exists. There is a variety of explanations: however, much of the elegant mathematical machinery they invoke to bring the physical world into being is not yet verifiable, nor is it expected to be, in the near future. Theories that speak of "quantum spacetime foam" or "inflation driven by scalar fields" do not have a substantive body of supporting data. Scientists who are investigating these novel ideas are the first to recognize the need for maintaining objectivity in the face of seemingly successful and logical explanations for our universe's existence. As Sheldon Glashow (1987) points out, we must continue to be watchful against "beautiful" theories that have no verifiable predictions, lest we find ourselves spinning fairy tales.

Unlike the pre-creation scenarios of our ancestors, modern science considers development of the universe following the Big Bang a process of successive "crystallization" as the universe cools. In a mathematically precise way, each stage brings into being new forces and particles that were once indistinguishable. Development appears to be a mindless, though logical, process that operates on matter to find the lowest energy state or configuration consistent with fundamental laws. Yet there is nothing about matter that seems to dictate whether it becomes a neuron or a dust mote, a star or a human being. Atoms are not tagged as animate or inanimate. Although a thoroughgoing reductionism can help us uncover the fields and mechanisms that define and constitute a universe, it is only by considering synergistic and collective phenomena that the rich and variegated world we live in begins to emerge.

Science is only now on the threshold of being able to study collective phenomena in detail, due largely to computers that can handle the enormous computations required to reach from the principles of matter into its collective properties. Only during the last 10 years has it been found that even inanimate systems, when constrained to follow a simple set of rules, lead to highly complex phenomena and "behavior." For example, recent computer designs, patterned after human neural networks, begin with a complicated pattern of electrical interconnections and a simple rule for modifying these interconnections based on the inputs they receive. Such systems spontaneously evolve, through dynamic self-interaction, into networks that recognize patterns and store information in the same way as simple organisms. These abilities are not preprogrammed, but emerge as the network interacts with the "outside" world. It would seem, then, that science may be on the threshold of describing not only the origin of our physical world, but the emergence of cognitive, replicating systems—that is, sentient life—within it.

In spite of the remarkable breadth and depth of the scientific exploration of the physical world, there is a sadness associated with it. To the extent that the essences and principles of reality can be described logically, only practitioners of science seem to have the skills or interest to follow intricate explanations and to understand their limitations. Many scholars in my profession realize that the modern story of creation has little meaning to the nonspecialist, since too much of the telling rests on subtle physical ideas, and demands a certain level of science literacy. The late Richard Feynman (1965) noted that

> "Every one of our laws [of nature] is a purely mathematical statement in rather complex and abstruse mathematics. . . . it is impossible to explain honestly the beauties of the laws of nature in a way that people can feel, without their having some deep understanding of mathematics. I am sorry but this seems to be the case" (39–40).

Steven Weinberg (1986), reflecting on the early progress in observational cosmology, writes: "This is often the way it is in physics—our mistake is not that we take our theories too seriously, but that we do not take them seriously enough. It is always hard to realize that these numbers and equations we play with at our desks have something to do with the real world" (169). This viewpoint is also expressed by Eugene Wigner (1960), who spoke of the "unreasonable effectiveness of mathematics in the physical sciences." Nowhere else in physics do we face this dilemma as frequently as when we consider the origin of the universe and the nature of matter. No other system of thought has demonstrated the same consistent level of insight into the details of physical reality as logical deduction coupled with the scientific method.

Many people feel that details of the origin of the physical world should be easy to understand. But simplicity manifests itself most clearly only to specialists who, over decades grapple with such details. It is indeed a challenge for a scientist to explain rainbows and other common phenomena without using the technical language of science (which, I might add, has taken more than three centuries to acquire). Unlike some religious concepts, based on everyday analogies (often of the human person), to the extent that science provides detailed explanations with mathematical models, it becomes rather boring for most human beings. This is unfortunate, since by knowing the context of our physical existence some of the "magic" of life can be recaptured, based on fact rather than on anthropocentric, even wishful, thinking.

As I write these words, light reflects from the page and delineates, by its absence, my words. Photons swim across an ever-changing sea of space and end their brief existence on my retina. What a glorious thought to ponder—that out of this invisible space there could spring into being a billion unseen universes. Some may vanish in a twinkling; some may be stillborn accidents of unfavorable laws. However, others may teem with sentient matter a billion years hence—long after we, have died and our universe has vanished back into the shimmering fabric of space.

NOTES

1. *Spacetime* describes the true arena for relativistic physics. Mathematically, one may not define time and space as independently observable aspects of the physical world, particularly if observers are in motion relative to one another. Normal spacetime is a four-dimensional continuum (or manifold) composed of three dimensions of space and one dimension of time, which, according to general relativity, may become deformed or curved in the presence of such matter as planets or stars. It is this deformation that causes bodies to move along curved paths through space.

2. A *field* is a mathematical or physical quantity whose properties are specified at each point in space. A common example is the temperature field of weather forecasters, showing (say) the noon temperature in every city in the United States. Velocity and pressure fields, as well as precipitation levels, are other examples from meteorology. For the physicist, gravity is a field whose magnitude varies in a precise manner at each point in space. The same is true for other fundamental forces in nature.

3. A *quantum field* is an extension of the concept that emphasizes the discrete character of the field that causes each force. In quantum field theory, every force is transmitted by the exchange of particles, called bosons, whose properties determine the characteristics of the force, such as its strength, range, and whatever aspect of matter the force acts upon.

4. A *GeV* is a unit of energy equal to 0.006 ergs, the energy produced by annihilating a single proton, or the typical energy of particles in a gas heated to 10 trillion degrees Kelvin.

5. Other supersymmetry theories distinguish between particles called inflatons (which cause the inflation) and the Higgs field (which breaks the symmetry) (Holman 1986). To have the Higgs field fulfill both functions leads to serious difficulties when the theory is asked to predict how galaxies are formed.

6. The elementary physical contents representing the speed of light, c, the strength of gravity, G, and the scale of quantum phenomena known as Planck's

constant, h, can be combined to give a representative length of 10^{-33} cm, and time, 10^{-43} sec. Theoreticians believe that these Planck scales reflect the level at which spacetime acquires quantum characteristics in the sense described by quantum gravity theory.

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