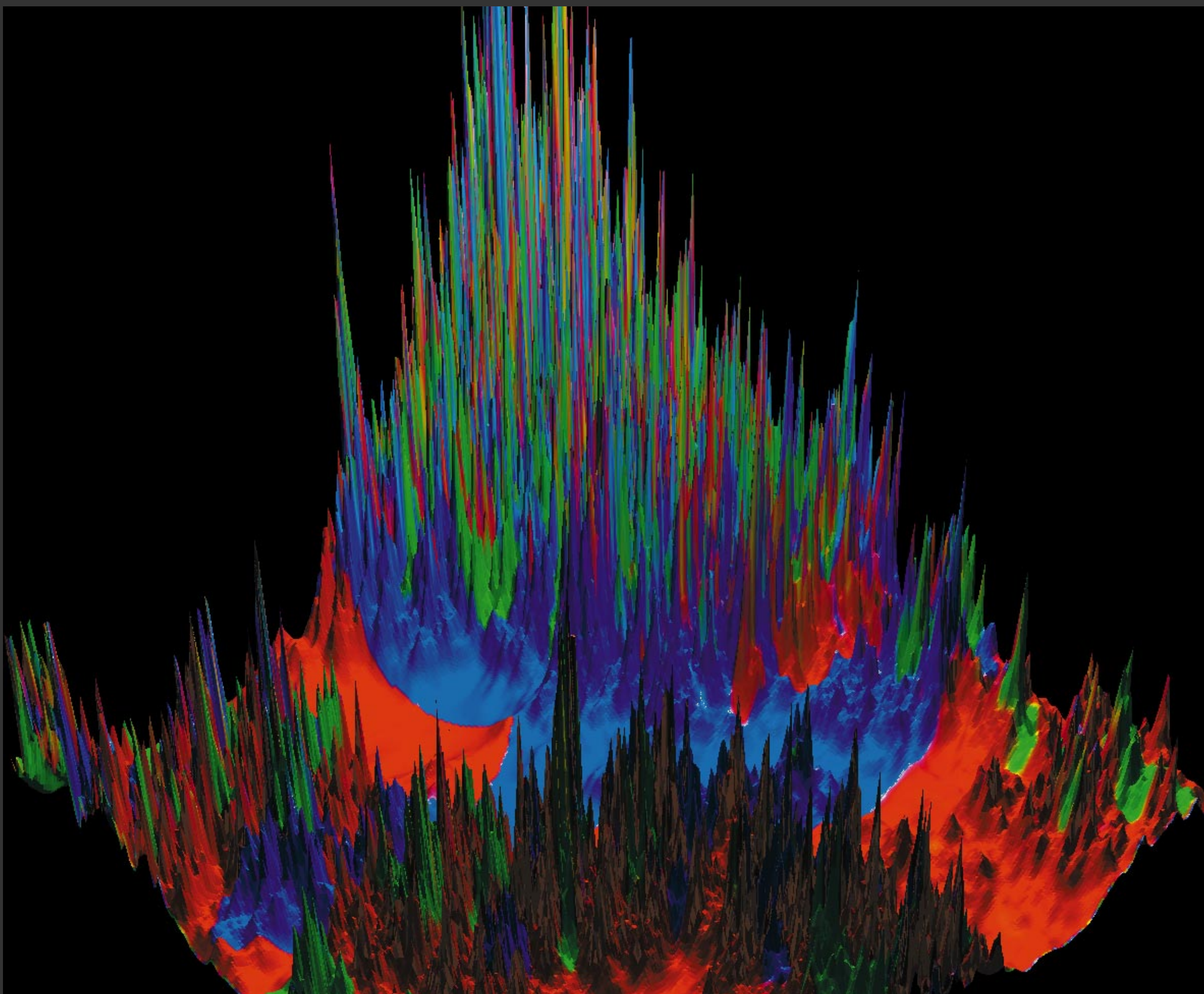
The Self-Reproducing Inflationary Universe



SELF-REPRODUCING UNIVERSE
in a computer simulation consists of exponentially large domains, each of which has different laws of physics (*represented by colors*). Sharp peaks are new "big bangs"; their heights correspond to the energy density of the universe there. At the top of the peaks, the colors rapidly fluctuate, indicating that the laws of physics there are not yet settled. They become fixed only in the valleys, one of which corresponds to the kind of universe we live in now.

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by Andrei Linde

If my colleagues and I are right, we may soon be saying good-bye to the idea that our universe was a single fireball created in the big bang. We are exploring a new theory based on a 15-year-old notion that the universe went through a stage of inflation. During that time, the theory holds, the cosmos became exponentially large within an infinitesimal fraction of a second. At the end of this period, the universe continued its evolution according to the big bang model. As workers refined this inflationary scenario, they uncovered some surprising consequences. One of them constitutes a fundamental change in how the cosmos is seen. Recent versions of inflationary theory assert that instead of being an expanding ball of fire the universe is a huge, growing fractal. It consists of many inflating balls that produce new balls, which in turn produce more balls, ad infinitum.

Recent versions of the inflationary scenario describe the universe as a self-generating fractal that sprouts other inflationary universes

Cosmologists did not arbitrarily invent this rather peculiar vision of the universe. Several workers, first in Russia and later in the U.S., proposed the inflationary hypothesis that is the basis of its foundation. We did so to solve some of the complications left by the old big bang idea. In its standard form, the big bang theory maintains that the universe was born about 15 billion years ago from a cosmological singularity—a state in which the temperature and density are infinitely high. Of course, one cannot really speak in physical terms about these quantities as being infinite. One usually assumes that the current laws of physics did not apply then. They took hold only after the density of the universe dropped below the so-called Planck density, which equals about 10^{94} grams per cubic centimeter.

As the universe expanded, it gradually cooled. Remnants of the primordial cosmic fire still surround us in the form of the microwave background radiation. This radiation indicates that the temperature of the universe has dropped to 2.7 kelvins. The 1965 discovery of this background radiation by Arno A. Penzias and Robert W. Wilson of Bell Laboratories proved to be the crucial evidence in establishing the big bang theory as the preeminent theory of cosmology. The big bang theory also explained the abundances of hydrogen, helium and other elements in the universe.

As investigators developed the theory, they uncovered complicated problems. For example, the standard big bang theory, coupled with the modern theory of elementary particles, predicts the existence of many superheavy particles carrying magnetic charge—that is, objects that have only one magnetic pole. These magnetic monopoles would have a typical mass 10^{16} times that of the proton, or about 0.00001 milligram. According to the standard big bang theory, monopoles should have emerged very early in the evolution of the universe and should now be as abundant as protons. In that case, the mean density of matter in the universe would be about 15 orders of magnitude greater than its present value, which is about 10^{-29} gram per cubic centimeter.

Questioning Standard Theory

This and other puzzles forced physicists to look more attentively at the basic assumptions underlying the standard cosmological theory. And we found many to be highly suspicious. I will review six of the most difficult. The first, and main, problem is the very existence of the big bang. One may wonder, What came before? If space-time did not exist then, how could everything appear from nothing? What arose first: the universe or the laws determining its evolution? Explaining this initial singularity—where and when it all began—still remains the most intractable problem of modern cosmology.

A second trouble spot is the flatness of space. General relativity suggests that space may be very curved, with a typical radius on the order of the Planck length, or 10^{-33} centimeter. We see, however, that our universe is just about flat on a scale of 10^{28} centimeters, the radius of the observable part of the universe. This result of our observation differs from theoretical expectations by more than 60 orders of magnitude.

A similar discrepancy between theory and observations concerns the size of the universe, a third problem. Cosmological examinations show that our part of the universe contains at least 10^{88} elementary particles. But why is the universe so big? If one takes a universe of a typical initial size given by the Planck length and a typical initial density equal to the Planck density, then, using the standard big bang theory, one can calculate how many elementary particles such a universe might encompass. The answer is rather unexpected: the entire universe should only be large enough to accommodate just one elementary particle—or at most 10 of them. It would be unable to house even a single reader of *Scientific American,* who consists of about 10^{29} elementary particles. Obviously, something is wrong with this theory.

The fourth problem deals with the timing of the expansion. In its standard form, the big bang theory assumes that all parts of the universe began expanding simultaneously. But how could all the different parts of the universe synchronize the beginning of their expansion? Who gave the command?

Fifth, there is the question about the distribution of matter in the universe. On the very large scale, matter has spread out with remarkable uniformity. Across more than 10 billion light-years, its distribution departs from perfect homogeneity by less than one part in 10,000. For a long time, nobody had any idea why the universe was so homogeneous. But those who do not have ideas sometimes have principles. One of the corner-

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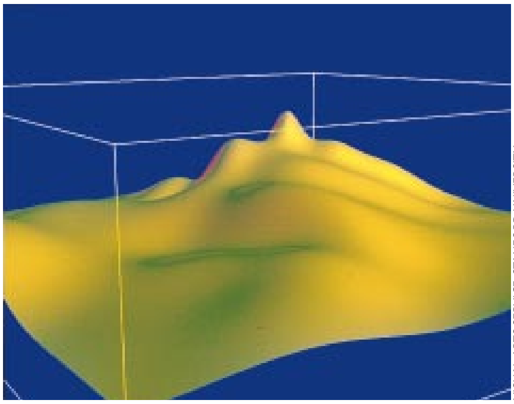

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EVOLUTION OF A SCALAR FIELD leads to many inflationary domains. In most parts of the universe, the scalar field decreases (*represented as depressions and valleys*). In other places, quantum fluctuations cause the scalar field to grow.

stones of the standard cosmology was the "cosmological principle," which asserts that the universe must be homogeneous. This assumption, however, does not help much, because the universe incorporates important deviations from homogeneity, namely, stars, galaxies and other agglomerations of matter. Hence, we must explain why the universe is so uniform on large scales and at the same time suggest some mechanism that produces galaxies.

Finally, there is what I call the uniqueness problem. Albert Einstein captured its essence when he said, "What really interests me is whether God had any choice in the creation of the world." Indeed, slight changes in the physical constants of nature could have made the universe unfold in a completely different manner. For example, many popular theories of elementary particles assume that space-time originally had considerably more than four dimensions (three spatial and one temporal). In order to square theoretical calculations with the physical world in which we live, these models state that the extra dimensions have been "compactified," or shrunk to a small size and tucked away. But one may wonder why compactification stopped with four dimensions, not two or five.

Moreover, the manner in which the other dimensions become rolled up is significant, for it determines the values of the constants of nature and the masses of particles. In some theories, compactification can occur in billions of different ways. A few years ago it would have seemed rather meaningless to ask why space-time has four dimensions, why the gravitational constant is so small or why the proton is almost 2,000 times heavier than the electron. Now developments in elementary particle physics make answering these questions crucial to understanding the construction of our world.

All these problems (and others I have not mentioned) are extremely perplexing. That is why it is encouraging that many of these puzzles can be resolved in the context of the theory of the self-reproducing, inflationary universe.

The basic features of the inflationary scenario are rooted in the physics of elementary particles. So I would like to take you on a brief excursion into this realm—in particular, to the unified theory of weak and electromagnetic interactions. Both these forces exert themselves through particles. Photons mediate the electromagnetic force; the *W* and *Z* particles are responsible for the weak force. But whereas photons are massless, the *W* and *Z* particles are extremely heavy. To unify the weak and electromagnetic interactions despite the obvious differences between photons and the *W* and *Z* particles, physicists introduced what are called scalar fields.

Although scalar fields are not the stuff of everyday life, a familiar analogue exists. That is the electrostatic potential—the voltage in a circuit is an example. Electrical fields appear only if this potential is uneven, as it is between the poles of a battery or if the potential changes in time. If the entire universe had the same electrostatic potential—say, 110 volts—then nobody would notice it; the potential would seem to be just another vacuum state. Similarly, a constant scalar field looks like a vacuum: we do not see it even if we are surrounded by it.

These scalar fields fill the universe and mark their presence by affecting properties of elementary particles. If a scalar field interacts with the *W* and *Z* particles, they become heavy. Particles that do not interact with the scalar field, such as photons, remain light.

To describe elementary particle physics, therefore, physicists begin with a theory in which all particles initially are light and in which no fundamental difference between weak and electromagnetic interactions exists. This difference arises only later, when the universe expands and becomes filled by various scalar fields. The process by which the fundamental forces separate is called symmetry breaking. The particular value of the scalar field that appears in the universe is determined by the position of the minimum of its potential energy.

Scalar Fields

Scalar fields play a crucial role in cosmology as well as in particle physics. They provide the mechanism that generates the rapid inflation of the universe. Indeed, according to general relativity, the universe expands at a rate (approximately) proportional to the square root of its density. If the universe were filled by ordinary matter, then the density would rapidly decrease as the universe expanded. Thus, the expansion of the universe would rapidly slow down as density decreased. But because of the equivalence of mass and energy established by Einstein, the potential energy of the scalar field also contributes to the expansion. In certain cases, this energy decreases much more slowly than does the density of ordinary matter.

The persistence of this energy may lead to a stage of extremely rapid expansion, or inflation, of the universe. This possibility emerges even if one considers the very simplest version of the theory of a scalar field. In this version the potential energy reaches a minimum at the point where the scalar field vanishes. In this case, the larger the scalar field, the greater the potential energy. According to Einstein's theory of gravity, the energy of the scalar field must have caused the universe to expand very rapidly. The expansion slowed down when the scalar field reached the minimum of its potential energy.

One way to imagine the situation is to picture a ball rolling down the side of a large bowl. The bottom of the bowl represents the energy minimum. The position of the ball corresponds to the value of the scalar field. Of course, the equations describing the motion of the scalar field in an expanding universe are somewhat more complicated than the equations for the ball in an empty bowl. They contain an extra term corresponding to friction, or viscosity. This friction is akin to having molasses in the bowl. The viscosity of this liquid depends on the energy of the field: the higher the ball in the bowl is, the thicker the liquid will be. Therefore, if the field initially was very large, the energy dropped extremely slowly.

The sluggishness of the energy drop in the scalar field has a crucial implication in the expansion rate. The decline was so

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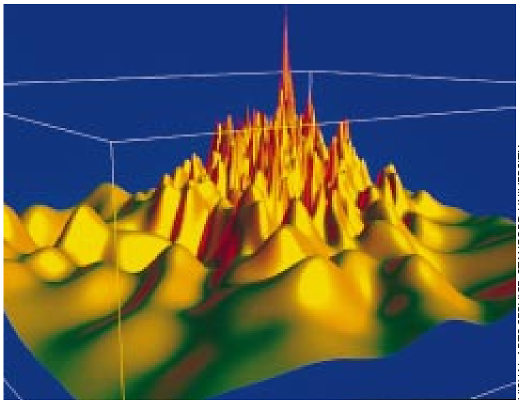
gradual that the potential energy of the scalar field remained almost constant as the universe expanded. This behavior contrasts sharply with that of ordinary matter, whose density rapidly decreases in an expanding universe. Thanks to the large energy of the scalar field, the universe continued to expand at a speed much greater than that predicted by preinflation cosmological theories. The size of the universe in this regime grew exponentially.



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UNIVERSE EXPANDS RAPIDLY in places—represented in the above model as peaks—where quantum fluctuations cause the scalar field to grow. Such expansion creates inflationary regions. In this model, we would exist in a valley, where space is no longer inflating.

This stage of self-sustained, exponentially rapid inflation did not last long. Its duration could have been as short as 10^{-35} second. Once the energy of the field declined, the viscosity nearly disappeared, and inflation ended. Like the ball as it reaches the bottom of the bowl, the scalar field began to oscillate near the minimum of its potential energy. As the scalar field oscillated, it lost energy, giving it up in the form of elementary particles. These particles interacted with one another and eventually settled down to some equilibrium temperature. From this time on, the standard big bang theory can describe the evolution of the universe.

The main difference between inflationary theory and the old cosmology becomes clear when one calculates the size of the universe at the end of inflation. Even if the universe at the beginning of inflation was as small as 10^{-33} centimeter, after 10^{-35} second of inflation this domain acquires an unbelievable size. According to some inflationary models, this size in centimeters can equal $10^{10^{12}}$—that is, a 1 followed by a trillion zeros. These numbers depend on the models used, but in most versions, this size is many orders of magnitude greater than the size of the observable universe, or 10^{28} centimeters.

This tremendous spurt immediately solves most of the problems of the old cosmological theory. Our universe appears smooth and uniform because all inhomogeneities were stretched $10^{10^{12}}$ times. The density of primordial monopoles and other undesirable "defects" becomes exponentially diluted. (Recently we have found that monopoles may inflate themselves and thus effectively push themselves out of the observable universe.) The universe has become so large that we can now see just a tiny fraction of it. That is why, just like a small area on a surface of a huge inflated balloon, our part looks flat. That is why we do not need to insist that all parts of the universe began expanding simultaneously. One domain of a smallest possible size of 10^{-33} centimeter is more than enough to produce everything we see now.

An Inflationary Universe

Inflationary theory did not always look so conceptually simple. Attempts to obtain the stage of exponential expansion of the universe have a long history. Unfortunately, because of political barriers, this history is only partially known to American readers.

The first realistic version of the inflationary theory came in 1979 from Alexei A. Starobinsky of the L. D. Landau Institute of Theoretical Physics in Moscow. The Starobinsky model created a sensation among Russian astrophysicists, and for two years it remained the main topic of discussion at all conferences on cosmology in the Soviet Union. His model, however, was rather complicated (it was based on the theory of anomalies in quantum gravity) and did not say much about how inflation could actually start.

In 1981 Alan H. Guth of the Massachusetts Institute of Technology suggested that the hot universe at some intermediate stage could expand exponentially. His model derived from a theory that interpreted the development of the early universe as a series of phase transitions. This theory was proposed in 1972 by David A. Kirzhnits and me at the P. N. Lebedev Physics Institute in Moscow. According to this idea, as the universe expanded and cooled, it condensed into different forms. Water vapor undergoes such phase transitions. As it becomes cooler, the vapor condenses into water, which, if cooling continues, becomes ice.

Guth's idea called for inflation to occur when the universe was in an unstable, supercooled state. Supercooling is common during phase transitions; for example, water under the right circumstances remains liquid below zero degrees Celsius. Of course, supercooled water eventually freezes. That event would correspond to the end of the inflationary period. The idea to use supercooling for solving many problems of the big bang theory was very attractive. Unfortunately, as Guth himself pointed out, the postinflation universe of his scenario becomes extremely inhomogeneous. After investigating his model for a year, he finally renounced it in a paper he co-authored with Erick J. Weinberg of Columbia University.

In 1982 I introduced the so-called new inflationary universe scenario, which Andreas Albrecht and Paul J. Steinhardt of the University of Pennsylvania also later discovered [see "The Inflationary Universe," by Alan H. Guth and Paul J. Steinhardt; SCIENTIFIC AMERICAN, May 1984]. This scenario shrugged off the main problems of Guth's model. But it was still rather complicated and not very realistic.

Only a year later did I realize that inflation is a naturally emerging feature in many theories of elementary particles, including the simplest model of the scalar field discussed earlier. There is no need for quantum gravity effects, phase transitions, supercooling or even the standard assumption that the universe originally was hot. One just considers all possible kinds and values of scalar fields in the early universe and then checks to see if any of them leads to inflation. Those places where inflation does not occur remain small. Those domains where inflation takes place become exponentially large and dominate the total volume of the universe. Because the scalar fields can take arbitrary values in the early universe, I called this scenario chaotic inflation.

In many ways, chaotic inflation is so simple that it is hard to understand why the idea was not discovered sooner. I think the reason was purely psychological. The glorious successes of the big bang theory hypnotized cosmologists. We assumed that the entire universe was created at the same moment, that initially it was hot and that the scalar field from the beginning resided close to the minimum of its potential energy. Once we

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began relaxing these assumptions, we immediately found that inflation is not an exotic phenomenon invoked by theorists for solving their problems. It is a general regime that occurs in a wide class of theories of elementary particles.

That a rapid stretching of the universe can simultaneously resolve many difficult cosmological problems may seem too good to be true. Indeed, if all inhomogeneities were stretched away, how did galaxies form? The answer is that while removing previously existing inhomogeneities, inflation at the same time made new ones.

These inhomogeneities arise from quantum effects. According to quantum mechanics, empty space is not entirely empty. The vacuum is filled with small quantum fluctuations. These fluctuations can be regarded as waves, or undulations in physical fields. The waves have all possible wavelengths and move in all directions. We cannot detect these waves, because they live only briefly and are microscopic.

In the inflationary universe the vacuum structure becomes even more complicated. Inflation rapidly stretches the waves. Once their wavelengths become sufficiently large, the undulations begin to "feel" the curvature of the universe. At this moment, they stop moving because of the viscosity of the scalar field (recall that the equations describing the field contain a friction term).

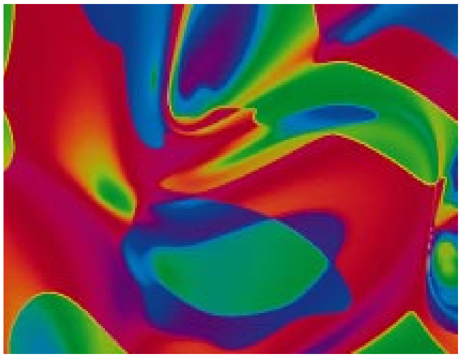
The first fluctuations to freeze are those that have large wavelengths. As the universe continues to expand, new fluctuations become stretched and freeze on top of other frozen waves. At this stage one cannot call these waves quantum fluctuations anymore. Most of them have extremely large wavelengths. Because these waves do not move and do not disappear, they enhance the value of the scalar field in some areas and depress it in others, thus creating inhomogeneities. These disturbances in the scalar field cause the density perturbations in the universe that are crucial for the subsequent formation of galaxies.

Testing Inflationary Theory

In addition to explaining many features of our world, inflationary theory makes several important and testable predictions. First, density perturbations produced during inflation affect the distribution of matter in the universe. They may also accompany gravitational waves. Both density perturbations and gravitational waves make their imprint on the microwave background radiation. They render the temperature of this radiation slightly different in various places in the sky. This nonuniformity was found in 1992 by the Cosmic Background Explorer (COBE) satellite, a finding later confirmed by several other experiments.

Although the COBE results agree with the predictions of inflation, it would be premature to claim that COBE has confirmed inflationary theory. But it is certainly true that the results obtained by the satellite at their current level of precision could have definitively disproved most inflationary models, and it did not happen. At present, no other theory can simultaneously explain why the universe is so homogeneous and still predict the "ripples in space" discovered by COBE.

Inflation also predicts that the universe should be nearly flat.



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KANDINSKY UNIVERSE, named after the Russian abstractionist painter, is depicted here as a swirling pattern that represents an energy distribution in the theory of axions, a kind of scalar field.

Flatness of the universe can be experimentally verified because the density of a flat universe is related in a simple way to the speed of its expansion. So far observational data are consistent with this prediction. A few years ago it seemed that if someone were to show that the universe is open rather than flat, then inflationary theory would fall apart. Recently, however, several models of an open inflationary universe have been found. The only consistent description of a large homogeneous open universe that we currently know is based on inflationary theory. Thus, even if the universe is open, inflation is still the best theory to describe it. One may argue that the only way to disprove the theory of inflation is to propose a better theory.

One should remember that inflationary models are based on the theory of elementary particles, and this theory is not completely established. Some versions (most notably, superstring theory) do not automatically lead to inflation. Pulling inflation out of the superstring model may require radically new ideas. We should certainly continue the search for alternative cosmological theories. Many cosmologists, however, believe inflation, or something very similar to it, is absolutely essential for constructing a consistent cosmological theory. The inflationary theory itself changes as particle physics theory rapidly evolves. The list of new models includes extended inflation, natural inflation, hybrid inflation and many others. Each model has unique features that can be tested through observation or experiment. Most, however, are based on the idea of chaotic inflation.

Here we come to the most interesting part of our story, to the theory of an eternally existing, self-reproducing inflationary universe. This theory is rather general, but it looks especially promising and leads to the most dramatic consequences in the context of the chaotic inflation scenario.

As I already mentioned, one can visualize quantum fluctuations of the scalar field in an inflationary universe as waves. They first moved in all possible directions and then froze on top of one another. Each frozen wave slightly increased the scalar field in some parts of the universe and decreased it in others.

Now consider those places of the universe where these newly frozen waves persistently increased the scalar field. Such regions are extremely rare, but still they do exist. And they can be extremely important. Those rare domains of the universe where the field jumps high enough begin exponentially expanding with ever increasing speed. The higher the scalar field jumps, the faster the universe expands. Very soon those rare domains will acquire a much greater volume than other domains.

From this theory it follows that if the universe contains at least one inflationary domain of a sufficiently large size, it begins unceasingly producing new inflationary domains. Inflation in each particular point may end quickly, but many other places will continue to expand. The total volume of all these domains will grow without end. In essence, one inflationary universe sprouts other inflationary bubbles, which in turn produce other inflationary bubbles.

This process, which I have called eternal inflation, keeps going as a chain reaction, producing a fractallike pattern of universes. In this scenario the universe as a whole is immortal. Each particular part of the universe may stem from a singu-

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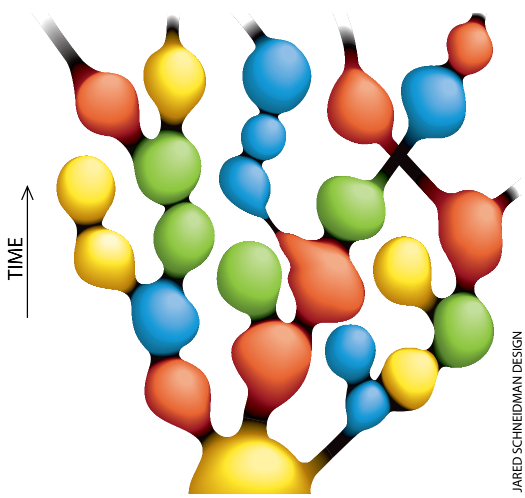
larity somewhere in the past, and it may end up in a singularity somewhere in the future. There is, however, no end for the evolution of the entire universe.

The situation with the very beginning is less certain. There is a chance that all parts of the universe were created simultaneously in an initial big bang singularity. The necessity of this assumption, however, is no longer obvious.

Furthermore, the total number of inflationary bubbles on our "cosmic tree" grows exponentially in time. Therefore, most bubbles (including our own part of the universe) grow indefinitely far away from the trunk of this tree. Although this scenario makes the existence of the initial big bang almost irrelevant, for all practical purposes, one can consider the moment of formation of each inflationary bubble as a new "big bang." From this perspective, inflation is not a part of the big bang theory, as we thought 15 years ago. On the contrary, the big bang is a part of the inflationary model.



SELF-REPRODUCING COSMOS appears as an extended branching of inflationary bubbles. Changes in color represent "mutations" in the laws of physics from parent universes. The properties of space in each bubble do not depend on the time when the bubble formed. In this sense, the universe as a whole may be stationary, even though the interior of each bubble can be described by the big bang theory.

In thinking about the process of self-reproduction of the universe, one cannot avoid drawing analogies, however superficial they may be. One may wonder, Is not this process similar to what happens with all of us? Some time ago we were born. Eventually we will die, and the entire world of our thoughts, feelings and memories will disappear. But there were those who lived before us, there will be those who will live after, and humanity as a whole, if it is clever enough, may live for a long time.

Inflationary theory suggests that a similar process may occur with the universe. One can draw some optimism from knowing that even if our civilization dies, there will be other places in the universe where life will emerge again and again, in all its possible forms.

A New Cosmology

Could matters become even more curious? The answer is yes. Until now, we have considered the simplest inflationary model with only one scalar field, which has only one minimum of its potential energy. Meanwhile realistic models of elementary particles propound many kinds of scalar fields. For example, in the unified theories of weak, strong and electromagnetic interactions, at least two other scalar fields exist. The potential energy of these scalar fields may have several different minima. This condition means that the same theory may have different "vacuum states," corresponding to different types of symmetry breaking between fundamental interactions and, as a result, to different laws of low-energy physics. (Interactions of particles at extremely large energies do not depend on symmetry breaking.)

Such complexities in the scalar field mean that after inflation the universe may become divided into exponentially large domains that have different laws of low-energy physics. Note that this division occurs even if the entire universe originally began in the same state, corresponding to one particular minimum of potential energy. Indeed, large quantum fluctuations can cause scalar fields to jump out of their minima. That is, they jiggle some of the balls out of their bowls and into other ones. Each bowl corresponds to alternative laws of particle interactions. In some inflationary models, quantum fluctuations are so strong that even the number of dimensions of space and time can change.

If this model is correct, then physics alone cannot provide a complete explanation for all properties of our allotment of the universe. The same physical theory may yield large parts of the universe that have diverse properties. According to this scenario, we find ourselves inside a four-dimensional domain with our kind of physical laws, not because domains with different dimensionality and with alternative properties are impossible or improbable but simply because our kind of life cannot exist in other domains.

Does this mean that understanding all the properties of our region of the universe will require, besides a knowledge of physics, a deep investigation of our own nature, perhaps even including the nature of our consciousness? This conclusion would certainly be one of the most unexpected that one could draw from the recent developments in inflationary cosmology.

The evolution of inflationary theory has given rise to a completely new cosmological paradigm, which differs considerably from the old big bang theory and even from the first versions of the inflationary scenario. In it the universe appears to be both chaotic and homogeneous, expanding and stationary. Our cosmic home grows, fluctuates and eternally reproduces itself in all possible forms, as if adjusting itself for all possible types of life.

Some parts of the new theory, we hope, will stay with us for years to come. Many others will have to be considerably modified to fit with new observational data and with the ever changing theory of elementary particles. It seems, however, that the past 15 years of development of cosmology have irreversibly changed our understanding of the structure and fate of our universe and of our own place in it. SA

The Author

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