

Unsolved question on cosmology

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AN ETERNITY OF BUBBLES?

by Alan Guth¹

If the inflationary theory of cosmology is right, it means that the universe is far larger than we had thought. Most likely the universe is also much older than we thought, and it includes not just one, but an infinity of big bangs.

The inflationary theory was developed to explain observable features of the universe, and it has been remarkably successful. One example is the nature of the cosmic background radiation, which cosmologists interpret as the afterglow of the heat of the big bang itself.

Astronomers have made high precision measurements of this radiation, finding that it arrives at Earth with the same intensity from all directions, to the extraordinary accuracy of about 1/1000 of a percent. Tracing the history of this radiation backwards in time, cosmologists conclude that the temperature and the density of matter in the universe must have been uniform to this accuracy when the cosmic background radiation was released, about 300,000 years after the big bang. Without inflation, this extreme uniformity of the early universe must be assumed, but cannot be explained. Calculations show that without inflation there would not have been nearly enough time for this uniformity to come about, so one is forced to assume, without explanation, that the universe was uniform from its very beginning.

Despite its name, the classical form of the big bang theory is not really a theory of a bang at all. It really describes only the aftermath of the bang. It describes how the early, hot, dense universe expanded and cooled; it describes how the light chemical elements were synthesized during this expansion, and how the matter coagulated to form galaxies and stars. But it says nothing about what banged or what caused it to bang, and therefore it makes no predictions about the uniformity of the universe just after the bang.

Inflation, on the other hand, can explain the “bang” of the big bang. It relies on a proposal, originating in modern particle physics, that extraordinarily high densities can lead to a form of matter that would turn gravity on its head, causing it to become repulsive rather than attractive.

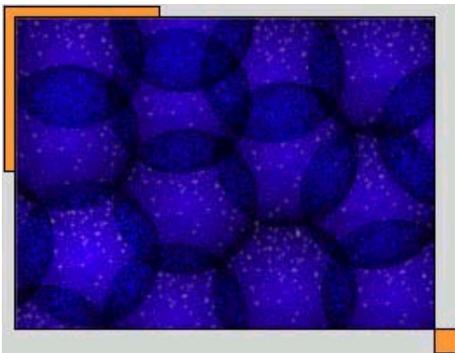
For reasons that are not important here, this form of matter is called a “false vacuum.” Inflation is the proposal that the expansion of the universe that we see today is the result of the gravitational repulsion of a false vacuum that filled the universe during a small fraction of a second of its early history.

In the inflationary theory the extreme uniformity of the universe was established early, before inflation began. At this time the region destined to become the presently observed universe was tiny—more than a billion times smaller than the size of a single proton. For such a small region, there was plenty enough time for uniformity to arise by the same kind of mundane processes by which the air in a room spreads out to uniformly fill the volume. After this uniformity was established, inflation took over to stretch the region to become large enough to include all the stars and galaxies that we see today.

Inflation not only explains the uniformity that we see in the cosmic background radiation, but it also explains the statistical properties of the very faint nonuniformities that have been observed with instruments so sensitive that they can measure minute variations of less than 1/1000 of a percent.

While inflation must be tested and judged on the basis of what it says about observable features of the universe, curiosity leads us to ask what inflation says about the universe as a whole. The answer is bizarre.

The gravitational repulsion of the false vacuum that is believed to have driven inflation is so strong that it would have launched a period of incredibly rapid expansion. The region would have doubled in size in about 10^{-37} (i.e., a decimal point followed by 36 zeroes and a 1) second. In the next 10^{-37} second it would have doubled again, and it would have kept doubling

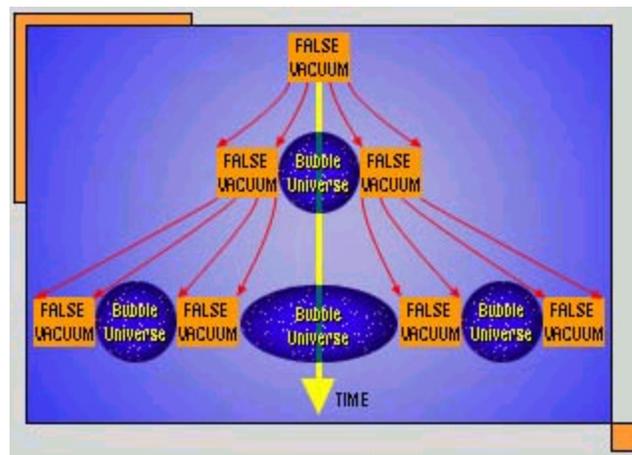


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every 10^{-37} seconds for as long as the false vacuum survived. The false vacuum is unstable, however, so at some point it “decayed,” converting its energy to a hot soup of ordinary particles. From this point onward the scenario would coincide with the standard hot big bang picture. The dramatic expansion, however, strongly suggests that the universe would be far larger than one would have otherwise imagined, so the observed part of the universe would be merely a speck in a much larger space.

But the whole story is much more complicated. The false vacuum is unstable, but in most versions of the theory it decays like a radioactive substance, such as radium. The decay is described by a half-life: half of the false vacuum will remain after one half-life, a quarter will remain after two half-lives, etc. However, unlike a radioactive material, the false vacuum would expand as it decayed, and the expansion would be faster than the decay. Although only half of the false vacuum would remain after one half-life, it would be larger than the initial region. The false vacuum would never disappear, but instead would continue increasing in volume indefinitely. Pieces of the false vacuum region would randomly decay, producing new “bubble” universes at an ever-increasing rate. Our universe would be just one of the universes on this infinite tree of bubbles.

The diagram on this page shows a simplified picture of how the evolution would work. The top bar illustrates a region of false vacuum. The second bar shows the same region one half-size later. I have assumed for illustration that it has enlarged by a factor of 4, but the actual factor could have been much larger. The second bar shows a region of false vacuum that has decayed, producing a bubble universe, and two regions that remain false vacuum. Each of these two remaining regions of false vacuum are as large as the original region. The third bar shows the region after another half-life has elapsed, with two more bubble universes formed from the false vacuum regions on the second bar, and four regions of false vacuum, each as large as the original. The process would go on forever. The bubbles would collide so rarely that any observer would have no more than a negligible probability of seeing any sign of the other bubbles’ existence. Nonetheless, an understanding of the infinite tree of universes seems to be needed in order to make statistical predictions about the properties of our own universe, which is assumed to be a typical “branch” on the tree.



In studying a scenario such as this, cosmologists generally assume that the laws of physics are the same throughout this multi-bubble universe. We don’t really have any way of knowing, but our goal is to understand the consequences of the laws of physics as we know them, and not to idly speculate about other mythical worlds. Nonetheless, there is a possibility that the other bubbles could be very different from our own. While empty space appears to be devoid of properties, to a modern particle physicist empty space, also called the vacuum, is an enormously complicated substance. Particle-antiparticle pairs are incessantly appearing and disappearing, and space itself is believed to break up into a poorly understood “quantum foam” when magnified enough so that distances as short as 10^{-33} centimeter become visible. Because of this complexity, physicists do not know whether only one kind of empty space is stable, or whether there are many kinds. Other kinds of space might not be three-dimensional, and they might alter the masses of elementary particles, or the forces that govern their behavior. If there are many kinds of space, the infinite tree of bubble universes would sample all the possibilities.

AN INHABITED UNIVERSE?

by Seth Shostak²



The soft lights from the stars on a summer night appear romantic, even enticing. But distance deceives us about the true nature of the universe. It is stupefyingly vast and depressingly empty. The cosmos is cold, silent, and brutally impersonal, a dark, three-dimensional canvas only occasionally punctuated by stars. From the surfaces of these glowing globes, scorching flames of gas lick the sky. Deep within the stars' interiors, elementary particles, unseen and unheard, wildly collide in response to the ferocious heat of a billion-year-old nuclear reaction.

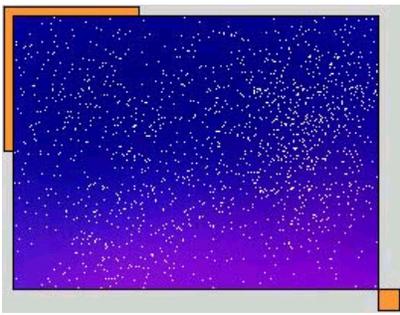
Extreme conditions are the norm. While the majority of the universe is a near-perfect vacuum, in some places matter overwhelms space. Where large stars have died or smashed together, the inexorable pull of gravity has crushed their raw materials into a volume that's smaller than a pinhead, smaller than an atom. In the vicinity of these so-called black holes, the very fabric of time and space is rent and twisted. These are truly the universe's most bizarre neighborhoods, the intellectual stomping grounds of Stephen Hawking.

Space is host to the most inhospitable environments imaginable. Nonetheless, there are subtle properties of the universe that allow the delicate process of life to exist. Indeed, it appears as if the cosmos has been "fine tuned" to permit life. Had the Big Bang happened more quickly, the early condensations of matter that led to galaxies, stars, planets and us would never have taken place. Had it happened more slowly, the universe would have quickly collapsed and disappeared. If the physical constants that govern the pace at which stars age and die were slightly different, life would not have had the time to evolve to produce you, me, or Stephen Hawking.

The entire universe has been constructed with one blueprint. Physics is the same throughout. So if biology has appeared here, around an unremarkable star in the outskirts of a run-of-the-mill galaxy, won't it have appeared manifold times elsewhere? After all, there are more stars visible to our telescopes than all the sand grains of Earth's beaches. Shouldn't we expect that life is a natural, frequent occurrence?

We don't yet know, but there is enticing evidence that what has happened on Earth may be the norm, and not the exception. In the past three years, astronomers have succeeded in finding planets around other stars. They have done this by measuring the subtle dance made by these stars in response to orbiting worlds. While scientists have long suspected that planets are common throughout the cosmos, they now have observational proof. And planets may be sweet oases in a hostile universe.

We believe that it is only on these tiny, cool worlds that the complex chemistry necessary for life can exist. It now seems probable that there are many such worlds. In August, 1996, a team of NASA and university researchers announced evidence for fossilized microbes in a meteorite that had been torn loose from the surface of Mars. This evidence suggests that billions of years ago, when the red planet was warmer and wetter, primitive life floated in its long-vanished oceans and rivers. Although controversial, this research implies that life could spring up on any half-decent planet. If it's true that Mars once sported biology, then life is a statistic, not a miracle.



Supposing that planets are common and life is easily begun, then perhaps the universe contains not only myriads of living creatures, but sophisticated societies as well. Perhaps the intelligent aliens that routinely appear in films and television have real counterparts in our galaxy.

How could we find such extraterrestrial beings? Rocketing off to other star systems is not feasible: Even with our fastest spacecraft, it would take more than 50,000 years to reach the nearest of these.

But nearly four decades ago, it was realized that while interstellar travel was expensive and time-consuming, interstellar

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communication might not be. Radio waves, particularly those at microwave frequencies, could easily penetrate the gas and dust between the stars. And even a modest signal, if properly beamed, would be sufficient to send a message from one star to another. Such signals would travel at the speed of light.

Scientists don't broadcast deliberate signals into space, hoping to stir the interest of nearby aliens. But what some astronomers have done for many years is to listen. They use large antennas (radio telescopes) connected to sophisticated digital receivers in the hope of eavesdropping on radio traffic that may already suffuse the star fields of our galaxy. This enterprise is known as SETI, the Search for Extraterrestrial Intelligence.

For nearly two decades, SETI was a NASA program, carried out by NASA centers in California. But in 1993, an amendment by Senator Richard Bryan of Nevada ended this effort. Since then, SETI has been a private endeavor, funded by individual donations.

The most ambitious search for cosmic company is known as Project Phoenix, and is conducted by the SETI Institute, in Mountain View, California. Phoenix scrutinizes the vicinities of about one thousand, nearby, sun-like stars for signals that are clearly of artificial origin. Since no one can be certain exactly where on the radio dial the aliens might be broadcasting, Phoenix carefully sifts through two billion narrow-band (1 Hz) channels between 1000 and 3000 MHz. It is in this spectral regime that the natural background noise from galaxies, quasars, and other celestial transmitters is minimal. It is a good band for a cosmic "hailing" signal.

So far, none of the SETI projects has booked success. Not a single, confirmed peep from the cosmos has been heard. But of course, that could change tomorrow, next week, or next year. If so, what would be the consequences?

To begin with, we would be confronted with one of the biggest news stories of all time. Unlike the daily reports of UFOs buzzing the countryside or of sex-starved aliens abducting citizens for salacious purposes, a signal detected by SETI researchers wouldn't rely on anecdote or unsteady home videos. It could be quickly and repeatedly confirmed by scientists world-wide. The signal itself would come under intense scrutiny, and new receivers would be built to check it for "fine structure"—rapid variations that might convey a message.

But even if such variations are found, it's unclear whether we would ever understand them. Humans have had radio technology for only a century, but any extraterrestrials we hear will more than likely have had it much longer. Their civilization will be far in advance of ours, perhaps by tens or hundreds of thousands of years. Only if they wish to educate us, to enlist us as members of some sort of "galactic club," will they make it easy for us to decode their signal. In that event, we could experience a transcendent moment in human history. We would be brought into the fold of a society beyond our abilities to imagine, and might leapfrog millennia of history.

But even if none of this happens, even if we never understand the signal that we receive, we would still know that in the desolate vastness of a brutally hostile cosmos, other thinking beings exist and thrive. In Stephen Hawking's universe, neither he nor we would be alone.

IS THERE A THEORY OF EVERYTHING?

by Michio Kaku³

When I was a child, I used to visit the Japanese Tea Garden in San Francisco. I would spend hours fascinated by the carp, who lived in a very shallow pond just inches beneath the lily pads, just beneath my fingers, totally oblivious to the universe above them. I would ask myself a question only a child could ask: What would it be like to be a carp?

What a strange world it would be! I imagined that the pond would be an entire universe, one that is two-dimensional in space. The carp would only be able to swim forwards and backwards, and left and right. But I imagined that the concept of “up”—beyond the lily pads—would be totally alien to them. Any carp scientist daring to talk about “hyperspace”—i.e., the third dimension “above” the pond—would immediately be labelled a crank.

I wondered what would happen if I could reach down and grab a carp scientist and lift it up into hyperspace. I thought, What a wondrous story that scientist would tell the others! The carp would babble on about unbelievable new laws of physics: beings who could move without fins; beings who could breathe without gills; beings who could emit sounds without bubbles.

I then wondered: How would a carp scientist know about our existence? One day it rained, and I saw the rain drops forming gentle ripples on the surface of the pond. Then I understood.

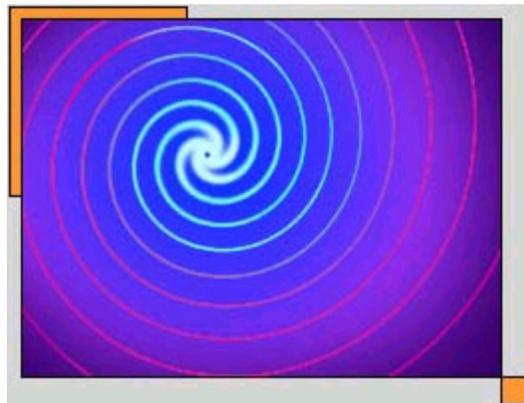
The carp could see rippling shadows on the surface of the pond. The third dimension would be invisible to them, but vibrations in the third dimensions would be clearly visible. These ripples might even be felt by the carp, who would invent a silly concept to describe this, called “force.” They might even give these “forces” cute names, such as light and gravity. We would laugh at them, because, of course, we know there is no “force” at all, just the rippling of the water.

Today, many physicists believe that we are the carp, swimming in our tiny pond, blissfully unaware of invisible, unseen universes hovering just above us in hyperspace. We spend our life in three spatial dimensions, confident that what we can see with our telescopes is all there is, ignorant of the possibility of 10-dimensional hyperspace. Although these higher dimensions are invisible, their “ripples” can clearly be seen and felt. We call these ripples gravity and light.

The theory of hyperspace, however, languished for many decades for lack of any physical proof or application. But the theory, once considered the province of eccentrics and mystics, is being revived for a simple reason: It may hold the key to the greatest theory of all time, the “theory of everything.”

Einstein spent the last 30 years of his life futilely chasing after this theory, the Holy Grail of physics. He wanted a theory that could explain the four fundamental forces that govern the universe: gravity, electromagnetism, and the two nuclear forces (weak and strong). It was supposed to be the crowning achievement of the last 2000 years of science, ever since the Greeks asked what the world was made of. He was searching for an equation, perhaps no more than one-inch long, that could be placed on a T-shirt, but was so powerful it could explain everything from the Big Bang, exploding stars, to atoms and molecules, to the lilies of the field. He wanted to read the mind of God.

Ultimately, Einstein failed in his mission. In fact, he was shunned by many of his younger compatriots, who would taunt him with the thought, “What God has torn asunder, no man can put together.”



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But perhaps Einstein is now having his revenge. For the past decade, there has been furious research on merging the four fundamental forces into a single theory, especially one that can meld general relativity (which explains gravity) with the quantum theory (which can explain the two nuclear forces and electromagnetism).

The problem is that relativity and the quantum theory are precise opposites. General relativity is a theory of the very large: galaxies, quasars, black holes, and even the Big Bang. It is based on bending the beautiful four-dimensional fabric of space and time. The quantum theory, by contrast, is a theory of the very small, i.e. the world of sub-atomic particles. It is based on discrete, tiny packets of energy called quanta.

Over the past 50 years, many attempts have been tried to unite these polar opposites, and have failed. The road to the Unified Field Theory, a.k.a. the “Theory of Everything,” is littered with the corpses of failed attempts.

The key to the puzzle may be hyperspace. In 1915, when Einstein said space-time was four-dimensional and was warped and rippled, he showed that this bending produced a “force” called gravity. In 1921, Theodor Kaluza wrote that ripples of the fifth dimension could be viewed as light. Like the fish seeing the ripples in hyperspace moving in their world, many physicists believe that light is created by ripples in five-dimensional space-time. But what about dimensions higher than 5?

In principle, if we add more and more dimensions, we can ripple and bend them in different ways, thereby creating more forces. In 10 dimensions, in fact, we can accommodate all four fundamental forces!

Actually, it’s not that simple. By naively going to 10 dimensions, we also introduce a host of esoteric mathematical inconsistencies (e.g., infinities and anomalies) that have killed all previous theories. The only theory which has survived every challenge posed to it is called superstring theory, in which this 10-dimensional universe is inhabited by tiny strings.

In fact, in one swoop, this 10-dimensional string theory gives us a simple, compelling unification of all forces. Like a violin string, these tiny strings can vibrate and create resonances or “notes.” That explains why there are so many sub-atomic particles: they are just notes on a superstring. (This seems so simple, but in the 1950s physicists were drowning in an avalanche of sub-atomic particles. J.R. Oppenheimer, who helped build the atomic bomb, even said, out of sheer frustration, that the Nobel Prize should go to the physicist who does NOT discover a new particle that year!)

Similarly, when the string moves in space and time, it warps the space around it, just as Einstein predicted. Thus, in a remarkably simple picture, we can unify gravity (as the bending of space caused by moving strings) with the other quantum forces (now viewed as vibrations of the string).

Of course, any theory with this power and majesty has a problem. This theory, because it is a theory of everything, is really a theory of Creation. Thus, to fully test the theory requires re-creating Creation!

At first, this might seem hopelessly impossible. We can barely leave the Earth’s puny gravity, let alone create universes in the laboratory. But there is a way out to this seemingly intractable problem. A theory of everything is also a theory of the everyday. Thus, this theory, when fully completed, will be able to explain the existence of protons, atoms, molecules, even DNA. The key is to fully solve the theory and test the theory against the known properties of the universe.

At present, no one on Earth is smart enough to complete the theory. The theory is perfectly well-defined, but, you see, superstring theory is 21st-century physics that accidentally fell into the 20th century. It was discovered purely by accident, when two young physicists were thumbing through a mathematics book. The theory is so elegant and powerful, we were never “destined” to see it in the 20th century. The problem is that 21st-century mathematics has not been invented yet.

But since physicists are genetically predisposed to be optimists, I am confident that we will solve the theory someday soon. Perhaps a young person reading this article will be so inspired by this story that he or she will finish the theory. I can’t wait!

IS TIME TRAVEL POSSIBLE?

by Michio Kaku

In H.G. Wells' novel, *THE TIME MACHINE*, our protagonist jumped into a special chair with blinking lights, spun a few dials, and found himself catapulted several hundred thousand years into the future, where England has long disappeared and is now inhabited by two groups of strange creatures, the Morlocks and the Eloi.

That may have made great fiction, but physicists have always scoffed at the idea of time travel, considering it to be the realm of cranks, mystics, and charlatans, and with good reason. However, rather remarkable advances in quantum gravity are reviving the theory; time travel has now become fair game for theoretical physicists writing in the pages of *PHYSICAL REVIEW* magazine.

One stubborn problem with time travel is that it is riddled with several types of paradoxes. For example, there is the paradox of the man with no parents: What happens when you go back in time and kill your parents before you are born? If your parents died before you were born, then how could you have been born to kill them in the first place?

There is also the paradox of the man with no past. For example, let's say that a young inventor is trying futilely to build a time machine in his garage. Suddenly, an elderly man appears from nowhere and gives the youth the secret of building a time machine. The young man then becomes enormously rich playing the stock market, race tracks, and sporting events because he knows the future. Then, as an old man, he decides to make his final trip back to the past and give the secret of time travel to his youthful self. Where did the idea of the time machine come from?

There is also the paradox of the man who is his own mother. (My apologies to science fiction writer Robert Heinlein.) "Jane" is left at an orphanage as a foundling. When "Jane" is a teenager, she falls in love with a drifter, who abandons her but leaves her pregnant. Then disaster strikes. She almost dies giving birth to a baby girl, who is then mysteriously kidnapped. The doctors find that Jane is bleeding badly, but, oddly enough, has both sex organs. So, to save her life, the doctors convert "Jane" to "Jim."

"Jim" subsequently becomes a roaring drunk, until he meets a friendly bartender (actually a time traveler in disguise) who whisks "Jim" way back into the past. "Jim" meets a beautiful teenage girl, then accidentally gets her pregnant with a baby girl. Out of guilt, he kidnaps the baby girl and drops her off at the orphanage. Later, "Jim" joins the time travelers corps, leads a distinguished life, and has one last dream: to disguise himself as a bartender to meet a certain drunk named "Jim" in the past. So, who is "Jane's" mother, father, brother, sister, grandfather, grandmother, and grandchild?

Not surprisingly, time travel has always been considered impossible. After all, Newton believed that time was like an arrow; once fired, it soared in a straight, undeviating line. One second on the earth was one second on Mars. Clocks scattered throughout the universe beat at the same rate.

Einstein gave us a much more radical picture. According to Einstein, time was more like a river, which meandered around stars and galaxies, speeding up and slowing down as it passed around massive bodies. One second on the earth was NOT one second on Mars. Clocks scattered throughout the universe beat to their own drummer.

However, before Einstein died, he was faced with an embarrassing problem. Einstein's neighbor at Princeton, Kurt Gödel, perhaps the greatest mathematical logician of the past 500 years, found a new solution to Einstein's own equations which allowed for time travel!

The "river of time" now had whirlpools in which time could wrap itself into a circle. Gödel's solution was quite ingenious: It postulated a universe filled with time that flowed like a rotating fluid. Anyone walking along the direction of rotation would find oneself back at the starting point, but backwards in time!

In his memoirs, Einstein wrote that he was disturbed that his equations contained solutions that allowed for time travel. But he finally concluded that the universe does not rotate, it expands (as in the Big Bang theory) and hence Gödel's solution could be thrown out for "physical reasons." (Apparently, if the Big Bang was rotating, then time travel would be possible throughout the universe!)

Then in 1963, Roy Kerr, a New Zealand mathematician, found a solution of Einstein's equations for a rotating black hole, which had bizarre properties. The black hole would not collapse to a point (as



previously thought) but into a spinning ring (of neutrons). The ring would be circulating so rapidly that centrifugal force would keep the ring from collapsing under gravity.

The ring, in turn, acts like Alice's Looking Glass. Anyone walking through the ring would not die, but could pass through the ring into an alternate universe. Since then, hundreds of other "wormhole" solutions



have been found to Einstein's equations. These wormholes connect not only two regions of space (hence the name) but also two regions of time as well. In principle, they can be used as time machines.

Recently, attempts to add the quantum theory to gravity (and hence create a "theory of everything") have given us some insight into the paradox problem.

In the quantum theory, we can have multiple states of any object. For example, an electron can exist simultaneously in different orbits (a fact which is responsible for giving us the laws of chemistry). Similarly, Schrödinger's famous cat can exist simultaneously in two possible states: dead and alive. So by going back in time and altering the past, we merely create a parallel universe. So we are changing someone ELSE's past by saving, for example, Abraham Lincoln from being assassinated at the Ford Theater, but our Lincoln is still dead. In this way, the river of time forks into two separate rivers.

But does this mean that we will be able to jump into H.G. Wells' machine, spin a dial, and soar several hundred thousand years into a future of some England?

No, or at least, not right now. There are a number of difficult hurdles to overcome. First, the main problem is one of energy. In the same way that a car needs gasoline, a time machine needs to have fabulous amounts of energy. One either has to harness the power of a star, or to find something called "exotic" matter (which falls up, rather than down) or find a source of negative energy. (Physicists once thought that negative energy was impossible. But tiny amounts of negative energy have been experimentally verified for something called the Casimir effect, i.e. the energy created by two parallel plates.) All of these are exceedingly difficult to obtain in large quantities, at least for several more centuries!

Then there is the problem of stability. Kerr's rotating black hole, for example, may be unstable if one falls through it. Similarly, quantum effects may build up and destroy the wormhole before you enter it. Unfortunately, our mathematics is not powerful enough to answer the question of stability because you need a "theory of everything" which combines both quantum forces and gravity. At present, superstring theory is the leading candidate for such a theory. (Actually, it is the ONLY candidate; it really has no rivals at all.) But superstring theory, which happens to be my specialty, is still too difficult to solve completely. The theory is well-defined, but no one on earth is smart enough to solve it.

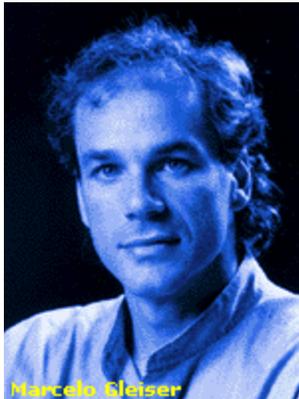
Interestingly enough, Stephen Hawking once opposed the idea of time travel. He even claimed he had "empirical" evidence against it. If time travel existed, he said, then we would have been visited by tourists from the future. Yet we see no tourists from the future. Ergo: time travel is not possible.

Because of the enormous amount of work done by theoretical physicists within the last five years or so, Hawking has since changed his mind, and now believes that time travel is possible (although not necessarily practical). Furthermore, perhaps we are simply not very interesting to these tourists from the future. Anyone who can harness the power of a star would consider us to be very primitive. Imagine your friends coming across an ant hill. Would they bend down to the ants and give them trinkets, books, medicine, and power? Or would some of your friends have the strange urge to step on a few of them?

In conclusion, don't turn someone away who knocks at your door one day and claims to be your future great-great-great-granddaughter. She may be right.

WHERE DOES MATTER COME FROM?

by Marcelo Gleiser⁴



It is said, and rightly so, that cosmology is the branch of physics that asks the grandest questions. After all, few questions within science can equal the impact of: “Where does the universe come from?” or “What is the fate of the universe” or “Where does the matter we are made of come from?”

But perhaps even more exciting than asking these questions is the fairly recent power that we have of answering them, at least partially, through a rational study of nature.

Most of us learned in high school that matter is made of atoms and that atoms are made of protons, neutrons and electrons. What we don’t usually learn in high school is that to each particle of matter there is another particle, an “anti-particle,” which is essentially the same as the particle but with opposite electric charge.

Thus, the negatively charged electron has its “anti-electron,” called a positron, which has positive electric charge; the proton has an anti-proton, and so on. Now comes the interesting part. According to the laws of particle physics, matter and antimatter should be present in the universe in equal amounts. And yet, we have ample observational evidence that, at least in a very large volume that surrounds us and extends far beyond our galaxy, there is much more matter than antimatter.

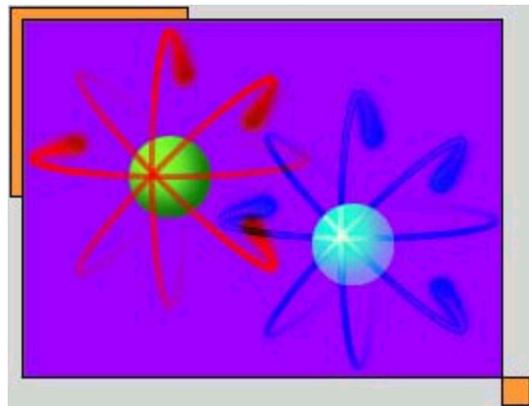
When particles collide with their anti-particles, the effects are devastating; they both disintegrate into electromagnetic radiation, their energy carried away in neutral particles called photons. In other words, if there were as much antimatter as matter in the universe, we wouldn’t be here to ask grand questions. The universe is somehow unbalanced, biased toward the existence of matter over antimatter. One of the greatest challenges in modern cosmology is to unveil the roots of this cosmic imperfection.

As with any scientific explanation, we need a few “basic ingredients,” a minimum amount of knowledge from which to build our models. The first ingredient we need is the Big Bang model of cosmology. According to this model, a small fraction of a second after the “beginning,” many kinds of particles and their anti-particles, in equal amounts, roamed about and collided with each other immersed in tremendous heat, as in a cosmic minestrone soup.

In this hot cosmic furnace, many different types of particles were being cooked, not necessarily the familiar quarks (the constituents of protons and neutrons) or electrons. As the universe expanded and cooled, a sort of selection mechanism not only biased the creation of quarks and electrons over other types of particles, but also generated the excess number of particles over anti-particles. Surviving the annihilation with their antimatter cousins, these excess particles organized themselves into more complex structures, until eventually atoms, mostly hydrogen, were formed when the universe was about 300,000 years old. The mystery, then, is to understand what kind of physics could generate this bias.

At first, resolving this question seems impossible. How can we possibly understand the mechanism that selected the existence of matter over antimatter during the earliest stages of evolution of the universe? In 1968, Andrei Sakharov, best known as the father of the Soviet bomb, proposed a recipe to generate more matter than antimatter in an expanding universe.

He suggested that three conditions must be satisfied in order to produce the matter excess. First, there must be a way of creating both more matter and antimatter particles of the kinds which are important to us—



⁴ Dr. Marcelo Gleiser, Associate Professor of Physics and Astronomy at Dartmouth College, is the author of *THE DANCING UNIVERSE: FROM CREATION MYTHS TO THE BIG BANG*, already a best-seller in his native Brazil and published in October 1997 in the U.S.A.

that is, the kinds that make up the atoms we are made of. Then, there must be a mechanism to bias the creation of more matter than antimatter. And finally, once we have an excess of matter particles over their antimatter partners, we must make sure that this excess is not erased as the universe continues to expand.

The first of these conditions is the creation of both baryons and anti-baryons from collisions involving the other particles present in the primordial soup. Baryons are particles which interact via the strong nuclear force, the force responsible for holding the nucleus together. Protons and neutrons (a.k.a. nucleons), and their constituent parts called quarks, are all baryons. At low energies, the number of baryons participating in collisions between different particles is conserved: that is, just like electric charge, the total number of baryons before an interaction equals the total after. If we are interested in making baryons, as we must in order to create matter in the universe, this conservation law is not very useful. According to Sakharov's requirement, however, at very high energies the interactions between elementary particles should not conserve the number of baryons. That is, at high energies both baryons and anti-baryons can be created from "other" particles. These high energies are naturally realized in the hot furnace of the early universe.

But this first condition does not differentiate between baryons and anti-baryons. At high temperatures we could still create the same number of each, and that wouldn't cause a bias toward matter over antimatter. We need a second condition. Once the high energies of the early universe allow for the creation of baryons and anti-baryons, we need a condition that selects, or biases, the creation of baryons over anti-baryons, an arrow pointing in the correct direction (i.e., toward matter).

In 1964, J.H. Christenson and his collaborators found experimental evidence that interactions between certain baryons do indeed exhibit this bias.

It is as if Nature has its own biases, in this case toward more baryons. If this is true in laboratory experiments, no doubt this will also be true in the early universe. Making excess matter over antimatter is not as hard as it initially seemed to be. But this is still not the whole story. One more challenge remains, which has to do with the physics of hot systems, also known as thermodynamics.

One of the properties of very hot systems is that they have no memory of their past. Imagine a coffee spoon which is initially cold. Now immerse one of its ends into a very hot cup of coffee. What happens? Although initially only the end in the coffee will be hot, very quickly the whole spoon will be equally hot. You won't be able to tell which of the two ends was immersed into the coffee cup; the system (coffee spoon and hot coffee) lost its "memory." Another term for this loss of memory is thermal equilibrium. If the early universe was in thermal equilibrium, any excess baryons would have been deleted; in equilibrium, the net baryon number is zero. In order to maintain the baryon bias as the universe cools, we need to make sure the universe doesn't "lose its memory" and delete the new baryons. Therefore, we need a third condition.

We need what are called "out of equilibrium" conditions. In order to "freeze" the net number of baryons produced by the first two conditions, the early universe could not have been always in thermal equilibrium. We are very familiar with systems that are out of thermal equilibrium in our everyday life. An example is condensation of steam. More specifically, imagine a container filled with hot steam which is immersed into a large bucket with cold water. The steam, being too hot compared with the cold water, is out of thermal equilibrium. In order to attain equilibrium it will go through a phase transition; the steam will cool down and condense, going from a gas phase to a liquid phase. As it does so, we will observe the appearance of droplets of the liquid phase that will grow and coalesce. The phase transition ends when the steam is completely converted into water.

How does this reasoning apply to the early universe? Strange as this may sound, the universe also went through phase transitions. Particles—and their properties—are also sensitive to temperature. The standard model of particle physics successfully describes how particles interact at energies over a thousand times larger than nuclear energies. According to this model, at very high temperatures all particles but one, the so-called Higgs particle, have no mass, while at lower temperatures they acquire a mass through their interactions with the Higgs particle. We say that matter has two different "phases," above and below the temperature at which particles like the quarks and the electron acquire a mass.

Thus, as the temperature of the early universe dropped, it went through a phase transition, and particles gained their mass. Like water droplets in steam, droplets of the low temperature (massive) phase appeared within the high temperature (massless) phase, growing and coalescing, in a typical out-of-equilibrium phase transition. Since only in the high temperature phase are baryons created in excess over anti-baryons (recall that the first two conditions apply only at high temperatures), these excess baryonic particles will penetrate the droplets of the massive phase, like viruses invading cells, becoming the net baryon number in the low temperature phase. As the droplets grow and coalesce, the whole universe is converted into the massive phase, completing the phase transition. According to our current models of "baryogenesis," the

creation of the excess baryons occurred when the universe was about one thousandth of a billionth of a second old. The protons and neutrons we are made of are the fossils of this primordial event.

So is this it? Is our work finished? Far from it. The simplest particle physics models we have do not generate the observed excess of matter over antimatter. Even worse, our true understanding of the complicated dynamics of these phase transitions is at best incomplete, leaving many questions unanswered at the moment. We have the broad outline of an explanation for the generation of matter in the universe, but the details are far from being understood.

WHERE IS THE MISSING MATTER? by Carlos Frenk as told to Ellen Mendlow⁵

It's a very exciting time to be a cosmologist. There are great big fundamental questions that are unanswered yet: What is the universe made of? What bigger question could you ask? What's even more exciting is the realization that it's within our grasp to answer these questions. We've narrowed down the possibilities and we've got all the machinery in place to find the answer. And that answer is likely to be one that is unrivaled in the physical sciences in terms of beauty because of the prospect of being able to understand the formation of galaxies and the movements of cosmic structures—essentially the behavior of the cosmos as a whole—in terms of the properties of subatomic particles. We'll be able to explain the universe as the result of the properties of its most basic constituents.



Over the last 15 years or so, computer simulations have become the primary tool that theoreticians have at their disposal to understand the formation of galaxies and of structure in the universe. The aim of the simulations is to take what we call initial conditions, which is an early state of the universe, and then see how that primeval, amorphous state evolves into an approximation of the universe we can compare with current observational surveys. Through these simulations we can arrive at an understanding of what the universe is made of, how it is structured, and how it came to be.

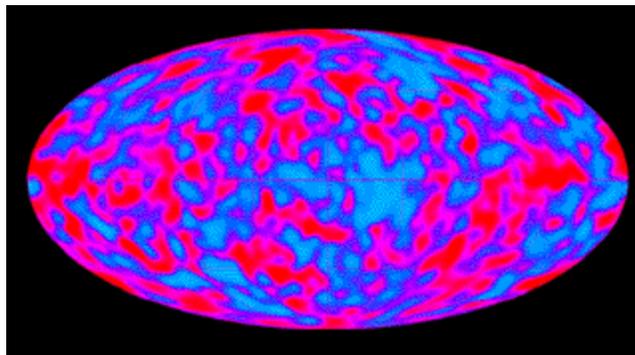
Computer-simulated universes are a very powerful tool because they allow you to produce material evidence for what various assumptions about the universe translate into, and then you can take this material evidence and compare it against reality. Because the universe is so complex, most mathematical treatments require many approximations and simplifications, so they are of limited applicability. Yet with a computer simulation you don't need to make any of those approximations. You solve the equations in the full generality, so it's a very appealing activity for theoreticians to do.

In the classic Einsteinian view of the universe, everything is smooth at the beginning and stays smooth forever. That clearly is not what our universe is doing because today our universe is very inhomogeneous—it is broken up into islands that we call galaxies and galaxy clusters. If the universe had been entirely smooth, we wouldn't be here to talk about it.

Instead, there must have been a small departure initially from this simplest assumption of a perfectly uniform universe. So the universe was not perfectly homogeneous either when it began or shortly after it began but, rather, it was slightly inhomogeneous. It had small regions where the density of matter was slightly higher than average and other regions where it was slightly lower than average. They were really tiny, these inhomogeneities, so tiny that for practical purposes it is hardly much of a departure from the simplest version of the theory. Yet tiny as they are to begin with, these inhomogeneities are very important because they are the seeds from which star clusters, galaxies and, eventually, human beings, will grow.

In April 1992, there was a very important discovery in cosmology that made the headline news all over the world—the discovery of ripples in the structure of the microwave background radiation. These ripples are nothing other than these little inhomogeneities we are talking about.

The COBE⁶ satellite that discovered these ripples was short-sighted—it had a very blurry vision of the early universe. The ripples that COBE saw were much larger than the



⁵ Dr. Carlos Frenk, a Mexican-born astrophysicist, is Professor of Astrophysics at Durham University, England. He is currently the Principal Investigator of the "Virgo consortium," a team of astrophysicists using supercomputers to simulate the universe.

⁶ COBE map shows ripples in the structure of the microwave background radiation

scales of the initial galaxies, so we haven't yet detected directly the progenitors of the galaxies in the large-scale structure in the microwave background, but we have discovered or we've directly imaged very closely related entities that correspond to larger structures today.

What goes into the computer simulation is the nature of the lumps that we've studied using the COBE satellite. And then the simulation follows the dynamic evolution of those small inhomogeneities as the universe expands and as it cools, taking these very tiny little lumps and making them grow bigger. As the process unfolds the lumps move around fairly quickly, and, as they do, some of them bump into each other and coalesce, and the computer follows these coalescences beautifully. Eventually one sees the mock universe grow from an almost, but not quite, homogeneous initial state to one which is really complex, irregular in structure and corresponding to the universe we see at the present day.

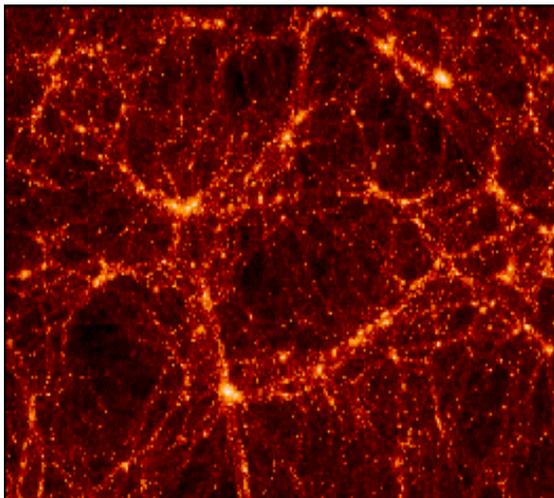
In the real universe, the whole evolutionary process is driven by gravity and gravity is produced by mass, so in order to create a simulated universe, we need to know what sort of mass our universe has. One of the critical discoveries of astronomers in the last 25 or 30 years is the realization that there must be more mass in the universe than is accounted for by what we can see.

That means most of the mass in the universe is made up of what we call dark matter, which simply describes matter that doesn't shine. To perform a successful computer simulation one needs to specify: what is the dark matter? What is it made of and how much is there?

The amazing thing is that if you make different assumptions you end up with different universes. So what many of us have been working on for the last 20 years is exploring various possibilities, evolving them in the computer to the present, and picking out those that look more like the real universe than others. Each mock universe that's made up in the computer can be compared with the real universe in a variety of ways. You could look at different properties of the real universe and you could ask, "How many lumps are there?" or "How big are the lumps?" or "How are the lumps distributed?" You then can ask corresponding questions in the real universe and compare the two.

There are various candidates for the dark matter, but today one of the most popular is a very exotic elementary particle we call a WIMP, or weakly interacting massive particle. The WIMPs are just elementary, subatomic particles—fundamental constituents of matter. Tiny little individual things, they themselves come basically in two types: the so-called hot dark matter and cold dark matter. Hot dark matter consists of quickly moving small particles such as neutrinos, a particle which may or may not have a mass and therefore may or may not contribute to the shape of the universe. Cold dark matter is made up of particles that are sluggish—they move more slowly and are therefore cold. Predicted in a certain class of theories of fundamental interactions called supersymmetric theories, they have yet to be discovered experimentally.

The reason many people believe the dark matter is a cold-dark-matter WIMP is precisely because the cold dark matter simulation that we can create in the computer looks a lot like the real universe, whereas every other possibility we've tried, including hot dark matter, has turned out to look nothing like the universe. When we started cold dark matter simulations over 15 years ago, our intention was to rule them out as a candidate.



We were following a methodology where you put forward a candidate with the goal of ruling it out in order to narrow down the possibilities. With cold dark matter we failed miserably in that sense. We haven't been able to rule it out. In all the calculations that we did and the many follow-ups people have done that have extended our work, they all come back to the same thing: cold dark matter universes look a lot like the real thing.

The fact that cold dark matter looks so good in a computer simulation doesn't prove, of course, that it is the force shaping the universe. Today it is the front runner candidate, but until we actually see a WIMP, we can't be sure. There are other possibilities that need to be explored and those can be explored within the context of computer simulations.

The key point of these theories is they require the existence of these hypothetical elementary particles. The proof of the pudding is in the eating; you have to capture one of these particles. So the ultimate test of this cold dark matter theory is to find the cold dark matter directly. Physics is, after all, an empirical, experimentally based human activity. You can't prove that something is correct by theory. The Greeks thought that the truth could be established by pure thought, but we now know better: the universe is not made that way. We cannot prove the reality of anything just by thinking about it.

It's hard to prove these particles exist because they're very weakly interactive; that's why they are dark: they don't interact with anything. Cold dark matter doesn't experience electromagnetic or nuclear interactions like protons and electrons do. They don't interact with your apparatus, so trying to detect them in the laboratory is like trying to catch water using a bucket full of holes; it just goes through it.

Still, there are experiments to detect even these very weakly interacting particles by side effects. If you have a semiconductor, occasionally one of the WIMPs could have a head-on collision with a silicon atom and cause the atom to recoil. Now these hits are very, very rare so you have to have several kilograms of semiconductor and you are trying to find one atom moving just because it gets hit by a WIMP. Until these experimental searches succeed we cannot be certain that the theories are correct. But the exciting part is that the experiments are in place and the particles are detectable. If they exist, we will know about them in a few years.

WHAT IS THE FUTURE OF COSMOLOGY?

by Lee Smolin⁷



Where are fundamental physics and cosmology going? It is of course, impossible to know for sure: This is science, where the ultimate worth of one's ideas is that they lead to a genuine understanding of nature. To be part of science, an idea or theory must make predictions that survive comparison with observation and experiment. Having said this, I can offer one scientist's view on the major themes in our search for the fundamental principles and laws that underlie the universe.

The most important principle of 20th-century physics is that all observable properties of things are about relationships. Even space and time must be spoken about in terms of relationships. There is no such thing as space independent of that which exists in it and no such thing as time apart from change. This is an old idea that philosophers such as Leibniz have argued for centuries, but general relativity is the first physical theory to be based on it. Many of the important problems facing theoretical physics have to do with the change from an absolute view of properties to this relational view. For example, I think it is highly likely that this is the key to further progress in string theory.

A very important part of turning cosmology into a science is to understand all the implications of a seemingly trivial statement: There is nothing outside the universe. One aspect of this is that there can be no observer outside the universe. We must understand the universe in a way in which the scientific description of it is a description made and used by observers who are part of the system itself. This seems to go against the idea that the scientific view of nature is objective, and an objective description is always based on observations of a system from outside. If cosmology is to be a science, we must invent a new notion of objectivity that allows the observers of the system also to be part of it.

Another aspect of this is that a scientific cosmology can contain no residue of the idea that the world was constructed by some being who is not a part of it. As the creatures who makes things, it is our most natural impulse to ask: When we come upon something beautifully or intricately structured, who made it? We must learn to give up this impulse if we are to do scientific cosmology. As there can, by definition, be nothing outside the universe, a scientific cosmology must be based on a conception that the universe made itself.

This is possible because, since Darwin, we know that structure and complexity can be self-organized. We understand that there are natural processes, easily comprehensible, by which organization can arise naturally and spontaneously, without any need for a maker outside of the system. This requires, however, that we take a more historical view of fundamental physics and cosmology. We must be open to the possibility that the answers to many of the questions we have about why the elementary particles or the fundamental forces are as they are—and not otherwise—may have answers that are, at least in part, historical.

This goes against the expectation that the more fundamental an explanation, the less historical it is. It also goes against the expectation that the ultimate answers to all questions about the elementary particles will be found with the discovery of a final, unified theory. This theory is presumed to be based on some mathematical principles that are both powerful and beautiful, in a way that will single it out for consideration as the unique possible fundamental theory. Our job, as physicists, is to discover this fundamental theory. We have implicitly believed that if we found it, it would be unique, so that there would be no room left to ask: Which fundamental theory holds true in our universe?

It hasn't turned out this way. The best candidate we have for a fundamental theory, string theory, comes in a great many versions, which each describe different possible universes with different elementary particles governed by different laws. As far as we know, all are equally consistent unified theories. So it seems like we do have to ask why one theory rather than another describes our universe.

It is possible that all these theories are aspects of a single theory. Recent work tends to suggest that they all describe something like different phases: Just as water molecules may be organized into a liquid, solid

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or gas, the fundamental “stuff” seems to come in a large number of different phases, which look to observers on large scales like different fundamental theories.

We are recently making some progress towards this unified string theory. Although its shape is not yet completely clear to us, it already has a name: “M” theory. Indeed, part of the search for this theory involves reformulating string theory in a way that is more relational, and less based on notions that space and time are absolute and independent of what exists. But it looks more and more like this theory will not allow the world to exist in a great many phases, and it will even be possible for the world to make a transition from one phase to another. Just as ice can be melted, it seems likely that in sufficiently energetic and violent events, the world may change from one phase to another, resulting in a change in the apparent laws of nature. Such violent events certainly include the approach to black hole singularities and the Big Bang of our universe.

Thus, rather than leading to the discovery of a single fundamental theory, string theory seems itself to point to the need to include an historical aspect in fundamental physics. If we want to know all the answers to our questions about electrons and protons, we are going to have to understand why the universe we see around us emerged from the Big Bang with one set of laws rather than another.

“We in the audience are all agreed that your theory is crazy. But what divides us is whether it is crazy enough.”

—NIELS BOHR, after listening to Wolfgang Pauli present a theory of everything.

I have proposed one possible answer: something like natural selection acts on the choice of the laws of physics. The basic idea is that black holes give rise to new regions of space and time, and that at these events, which resemble our Big Bang, the laws of physics can change. When worked out in detail, this idea leads to a scientific theory which makes predictions which are testable. The basic prediction is that no small change in the masses of the elementary particles or the strengths of the forces would lead to a world with more black holes than ours. So far, although a number of astronomers have tried to find counterexamples, this prediction has held up. I can also deduce from the theory that certain things will never be seen. For example, a neutron star with a mass at least three times that of our sun is incompatible with the theory. If one is seen, the theory is disproved!

It is also possible to imagine other ways in which historical elements could come into the laws of nature. Indeed, we are discovering that there it may be that space is itself the result of spontaneous processes of self-organization. Processes of self-organization other than natural selection have been studied by people like Per Bak and Stuart Kauffman for some time, and they are known to occur in a variety of situations. It may very well be that mechanisms like self-organized criticality, which Bak and Kauffman describe, may play a role in the emergence of space itself, from a complex primordial network of interactions.

This idea is being studied now by a number of people. Although it is too early to say if it will work, I can say something about how it comes about. The reason is that those of us studying the problem of combining general relativity with quantum theory have understood that the geometry of space must be discrete. Just like matter is made of atoms, space itself must be made of discrete bits.

This conclusion has arisen from several points of view. First of all, it seems to be required by the thermodynamics of black holes, as Jacob Bekenstein has been pointing out for years. It also seems to be implied by string theory, as Lenny Susskind and Gerard 'tHooft, among others, have been arguing. In the last few years we have also understood that the ultimate discreteness of space is loosely a consequence of combining the basic principles of quantum mechanics and general relativity. Thus, a few years ago, Carlo Rovelli and I were able to show that, rather generally, quantum gravity predicts that the volumes of regions in space and the areas of surfaces must come in discrete units, like the energy levels of atoms. We are even able to make precise predictions about the discrete units of area and volume.

This discovery was a great pleasure for us because we rediscovered a beautiful set of structures, called spin networks, that our theory tells us are descriptions of the discrete forms of space. These structures were originally invented by Roger Penrose more than thirty years ago, as a first guess of what a discrete geometry of space would look like. It has been very gratifying to be able to confirm that Penrose's intuition was essentially correct.

Once this is understood, we are faced with a new question: How do these discrete bits of space assemble themselves into a smooth structure that looks like the space we see around us? This turns out to be very much like asking why atoms often assemble themselves into solids, like plastics or metals, that look smooth when examined at scales larger than the atoms. It seems to be the case that without some special organization, the discrete bits of space—the networks—do not assemble themselves into big smooth

structures that could describe the featureless space we observe. Instead, they typically form chaotic structures that do not resemble any previous notion of space.

Thus, we are faced with the very real possibility that the fact that the world has any spatial extension at all is a contingent historical fact, that also requires explanation by some principle of self-organization. We are working on this now, and there seems to be good progress. I also expect that the outcome of this work will be a unification of the different approaches that have led to an expectation that space is discrete, including string theory and black hole thermodynamics. What for me is most provocative is the possibility that, for this to work, we will have to extend the Darwinian idea that the structure of a system must be formed from within by natural processes of self-organization—to the properties of space and time themselves.

In fact, there are other reasons to expect that space and time should be self-organized. Systems which are self-organized turn out to be complex systems. What is a complex system? What is complexity? One approach to this question, which Julian Barbour and I have developed, is to define the complexity of a system in terms of the variety of the interactions of the parts of the system. Roughly speaking, the more variety a system has, the easier it is to distinguish the parts of the system from each other by describing each of their neighborhoods. In these terms, a complex universe is one in which the view from every place is different from the view from any other place. But, as I argued at the beginning, space itself is defined only by the relationships among things. This means that the more complex a universe is, the easier it is to define space in terms of relationships. This means that there is a deep and fundamental connection between the idea that space and time are to be defined solely in terms of relationships and the idea that the world is a complex system whose structure is to be explained, in part, by its having undergone processes of self-organization.

The first is the key idea behind general relativity, the second the idea behind modern biology. What joins them is that in the end both sets of ideas make sense as descriptions of systems, like the universe or life on earth, that must structure themselves from the inside, without being made or observed from the outside.

But these themes are not only essential for understanding what is happening in cosmology and fundamental physics. More and more, I have the experience of meeting people in other fields who talk to me about the importance of the themes of relationalism, variety, evolution and self-organization in their own fields. First, in science, one sees the same constellation of themes reflected in the work of people such as Per Bak and Stuart Kauffman, who are attempting to understand the principles of self-organization at work in biology and other complex systems, such as the economy. One even sees these themes in the work of pure mathematicians, such as Louis Crane, John Baez and others, who are exploring the use of category theory as the basis of understanding topology, algebra and logic. Beyond science, if one reads political thinkers such as Drucilla Cornell or Roberto Unger; explores the architectural adventures of Frank Gehry and Charles Jencks; or looks at the sculpture and painting of artists like Saint Clair Cemin or Donna Moylan, one sees they also are captivated by the idea that the world is constructed from evolving relationships rather than eternal and static absolutes.

Of course, this does not mean that these ideas are right; only observation and experiment can, in the end, tell us that. But it does mean that the late twentieth century pessimists, the postmodernists and social constructivists, and the end-of-this-and-that-ists have it completely wrong. We enter the 21st century with new ideas and wide horizons, with much to do and everything to talk about.