When Fields Collide

The history of particle cosmology, a new branch of physics that has shed light on the origins of the universe, shows that science can sometimes benefit from wrenching changes

By David Kaiser

Particle cosmology, which investigates how the smallest units of matter have determined the shape and fate of the universe, is one of the hottest topics in physics today. In recent years the field has received as much as half a billion dollars in funding from the U.S. Department of Energy, the National Science Foundation and NASA. Scientists have made great strides in understanding the high-energy particle interactions that roiled the universe in the first moments of its history and influenced cosmic evolution in the billions of years afterward.

The dramatic success of particle cosmology is all the more striking given that this branch of research did not even exist 30 years ago. Before 1975, particle physics and cosmology were treated as separate fields of study (especially in the U.S.), and few scientists considered how discoveries in one specialty could enhance research in the other.

So why did particle cosmology arise? During the mid-1970s, researchers realized that studies of the early universe offered a unique window for investigating high-energy phenomena that cannot be recreated in the laboratory. But a series of changes in the funding and teaching of physics also helped to push cosmological questions to the forefront. The rapid emer-

FIRST EXPLOSIVE MOMENTS of cosmic history have been reconstructed by particle cosmologists, who study the birth of the universe.

SLIM FILMS

gence of particle cosmology illustrates how government budgets, educational institutions and even the publication of textbooks can radically alter the direction of research. The history of that era also shows that science can reap tremendous benefits when researchers move away from familiar subjects to tackle new challenges.

A good way to tell the story is to focus on the fortunes of two sets of ideas: the Brans-Dicke field, introduced by gravitational specialists, and the Higgs field, puzzled over by particle physicists. Both groups created these concepts in response to a problem that exercised many scientists during the late 1950s and early 1960s: why objects have mass. Although these two theories did not drive the union of particle physics and cosmology, the course of their development demonstrates how the two branches of research converged.

A Tale of Two φ's

MASS SEEMS LIKE such an obvious property of matter that one might not think it requires an explanation. Yet finding descriptions of mass that were compatible with other ideas from modern physics proved no easy feat. Experts on gravitation and cosmology framed the problem in terms of Mach's principle, named for Austrian physicist and philosopher Ernst Mach, a famed critic of Newton and an inspiration to the young Albert Einstein. A good approximation of Mach's principle might be phrased this way: an object's mass—a measure of its resistance to changes in its motion—ultimately derives from that object's gravitational interactions with all the other matter in the universe. Although this principle intrigued Einstein and spurred his thinking, his general theory of relativity ultimately departed from it.

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To incorporate Mach's principle into gravitational theory, scientists postulated the existence of a new scalar field that interacts with all types of matter. (A scalar field has one value for each point in space and time.) In 1961 Princeton University graduate student Carl Brans and his thesis adviser, Robert H. Dicke, pointed out that in Einstein's general relativity, the strength of gravity is fixed by Newton's constant, *G*. According to Einstein, *G* has the same value on Earth as it does in the most distant galaxies and does not change over time. Offering an alternative, Brans and Dicke suggested that Mach's principle could be satisfied if Newton's constant varied over time and space. They introduced a field called φ that was inversely proportional to Newton's constant and swapped $1/\varphi$ for *G* throughout Einstein's gravitational equations.

According to the Brans-Dicke theory, matter responds to the curvature of space and time, as in ordinary general relativity, *and* to variations in the local strength of gravity [*see top illustration in box on opposite page*]. The φ field permeates all of space, and its behavior helps to determine how matter moves through space and time. Any measurement of an object's mass therefore depends on the local value of φ. This theory was so compelling that members of Kip Thorne's gravity group at the California Institute of Technology used to joke that they believed in Einstein's general relativity on Mondays, Wednesdays and Fridays and in Brans-Dicke gravity on Tuesdays, Thursdays and Saturdays. (They remained agnostic on Sundays.)

Meanwhile, within the much larger community of particle physicists, the problem of mass arose in a different form. Beginning in the 1950s, theorists found that they could represent the effects of nuclear forces by imposing special classes of symmetries on the equations governing the behavior of subatomic particles. Yet the terms they would ordinarily include in these equations to represent particle masses violated the special symmetries. In particular, this impasse affected the *W* and *Z* bosons—the particles that give rise to the weak nuclear force, which is responsible for radioactive decay. If these force-carrying particles were truly massless, as the symmetries seemed to require, then the range of nuclear forces should have been infinite—two protons, for example, should have been able to exert a nuclear force on each other from across the galaxy. Such a long range flagrantly contradicted the observed behavior of nuclear forces, which fall off rapidly for distances larger than the size of atomic nuclei. Only if the force-carrying particles had some mass would the theoretically predicted range come into line with observations.

Many physicists focused on this conundrum, trying to formulate a theory that would represent the symmetry properties of subatomic forces while also incorporating massive particles. In 1961 Jeffrey Goldstone, then at the University of Cambridge, noted that the so-

Overview/A Revolution in Physics

- Until the 1970s researchers considered particle physics and cosmology to be completely separate fields of study.
- Sharp cutbacks in particle physics starting in the late 1960s prompted scientists to expand their horizons and explore topics in gravitation and cosmology.
- By the 1980s researchers had found that studying the early universe offered a new way to explore high-energy phenomena. Since then, the hybrid field of particle cosmology has become one of the most fruitful in physics.

lutions to the equations need not obey the same symmetries that the equations themselves do. As a simple illustration he introduced a scalar field, coincidentally labeled φ, whose potential energy density, $V(\varphi)$, bottoms out at two points: when φ has the values of $-v$ and $+v$ [*see bottom illustration in box at right*]. Because the energy of the system is lowest at these minima, the field will eventually settle into one of them. The potential energy is exactly the same for both values, but because the field must eventually land at just one value—either $-v$ or $+v$—the solution to the equations spontaneously breaks their symmetry.

In 1964 Peter W. Higgs of the University of Edinburgh revisited Goldstone's work and found that a theory with spontaneous symmetry breaking would allow for the existence of massive particles. The mass arises from interactions between the φ field and all types of particles, including those that generate the weak nuclear force. The equations governing these interactions, Higgs demonstrated, obey all the requisite symmetries. Before φ settles into one of the minima of its potential energy, the particles skip lightly along, merrily unencumbered. Once φ arrives at either $+v$ or $-v$, however, the newly anchored field exerts a drag on anything coupled to it—the subatomic equivalent of being mired in molasses. In other words, the force-carrying particles (as well as garden-variety matter such as electrons) start to behave as if they have a nonzero mass, and any measurements of their mass depend on the local value of φ.

The Brans-Dicke and Higgs papers were published at about the same time in the same journal, *Physical Review*. Both articles quickly became well known; to this day, both are among the most cited physics articles of all time. Each proposed to explain the origin of mass by introducing a new scalar field that interacted with all types of matter. Given the similarity of the proposals and the quick attention they both received, one might have expected physicists to consider them alongside each other. Yet this pairing rarely happened. Of the 1,083 articles that cited either

Separate Concepts of Mass

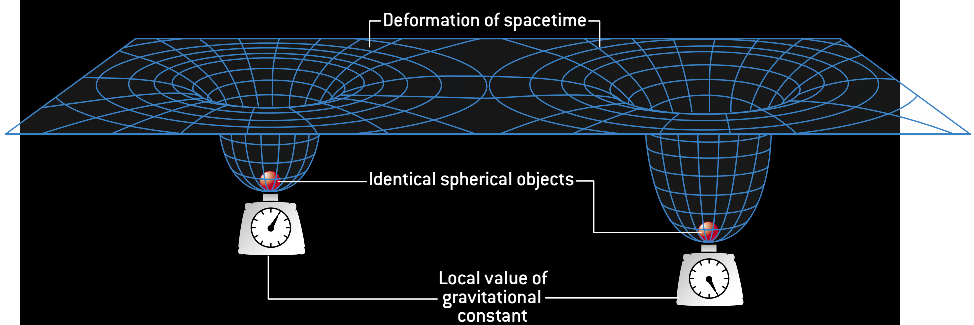
The barriers that divided physicists in the early 1960s are illustrated by their parallel attempts to explain why objects have mass. Although cosmologists and particle physicists proposed similar theories, few scientists saw the connection.

From Cosmology: Brans-Dicke Gravity

Carl Brans

Robert Dicke

▼ In 1961 Carl Brans and Robert Dicke of Princeton University proposed a field called φ that allows Newton's gravitational constant to vary over time and space. An object at a point in space where the constant is small (*left*) will be less massive—and warp the local spacetime less—than an identical object at a point where the constant is large (*right*).

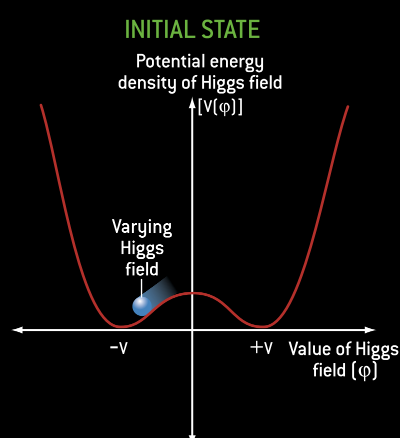


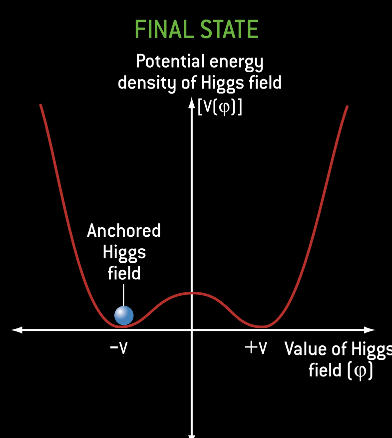
From Particle Physics: The Higgs Field

Jeffrey Goldstone

Peter Higgs

▼ In 1961 Jeffrey Goldstone, then at the University of Cambridge, introduced a field—also called φ, coincidentally—whose potential energy density $V(\varphi)$ bottoms out at two points, $-v$ and $+v$. Three years later Peter Higgs of the University of Edinburgh used this field to explain mass. Particles were massless at first when φ varied (*left*); they acquired mass only after φ settled into one of its minima (*right*).

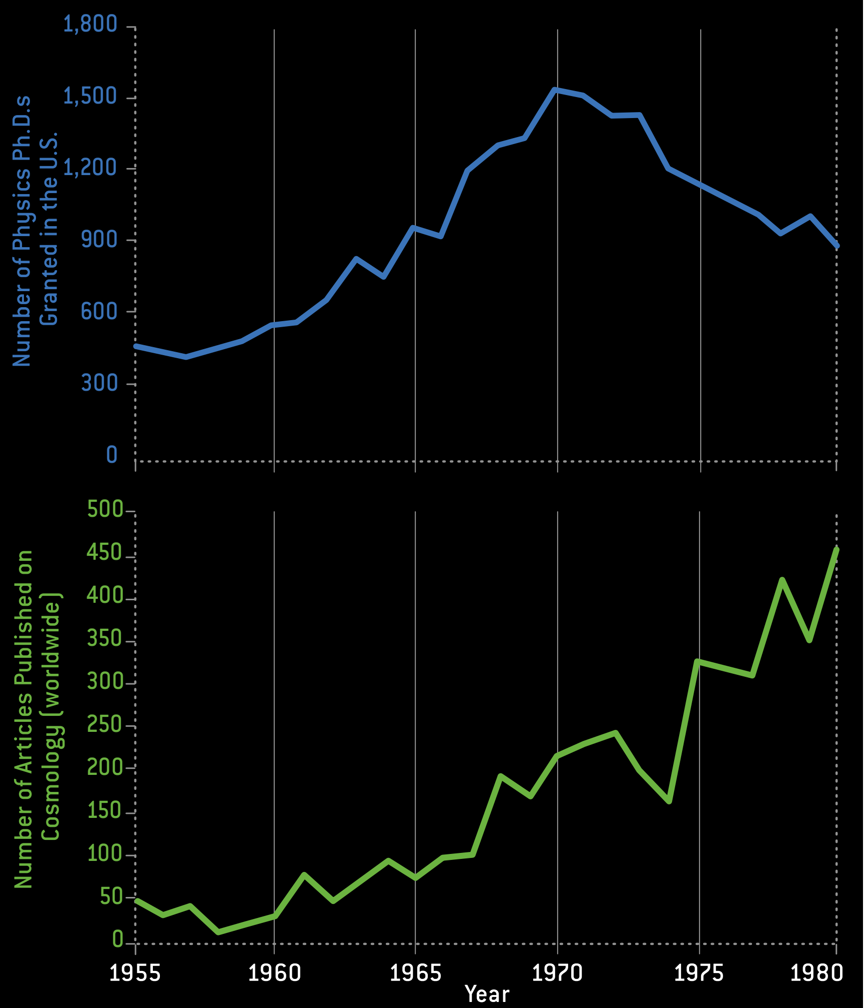




LUCY READING-IKKANDA (*field diagrams*); R. CRESSON *Luna* (*Brans*); BETTMANN/CORBIS (*Dicke*); AIP EMILIO SEGRÈ VISUAL ARCHIVES, PHYSICS TODAY COLLECTION (*Goldstone*); PETER TUFFY *Edinburgh University* (*Higgs*)

A Change of Topic

▼ Government support for physics boomed in the 1950s and 1960s but fell sharply in the late 1960s and 1970s. The number of new Ph.D.s plummeted as well (*top*). Many particle physicists, who were hit hardest, shifted their attention to cosmology. Research in that field blossomed (*bottom*).



LUCY READING-IKKANDA

the Brans-Dicke or Higgs paper between 1961 and 1981, only six—less than 0.6 percent—included both articles in their references. (The earliest instance was in 1972, and the rest came after 1975.) This mutual ignorance highlights the stark boundaries that existed at the time between the particle physicists and the specialists in gravitation and cosmology.

Pushes, Pulls and Pedagogy

CLEARLY, the two communities saw different things in their respective φ's. To the experts in gravitation and cosmology, the Brans-Dicke field (φ_{BD}) was exciting because it offered an alternative to Einstein's general relativity. To the particle physicists, the Higgs field (φ_H) was exciting because it offered hope that their theories might be able to explain the behavior of nuclear forces among massive particles. Before the mid-1970s, nobody suggested that φ_{BD} and φ_H might be physically similar or even worth examining side by side.

The divide between particle physics and cosmology was especially sharp in the U.S. when Brans, Dicke, Goldstone and Higgs introduced their respective φ's. The Physics Survey Committee of the National Academy of Sciences, for example, issued a policy report in 1966 that recommended doubling the funding and Ph.D.-level personnel for particle physics over the next few years but called for virtually no expansion in the already small areas of gravitation, cosmology and astrophysics. Furthermore, even though some of the Soviet textbooks published on gravity during that era included speculations about nuclear forces, such mixing of genres was absent from American textbooks.

These research patterns, however, would change radically by the late 1970s. Looking back on the swift rise of particle cosmology, physicists almost always point to two important developments that spurred the merger: the discovery of asymptotic freedom in 1973 and the construction of the first grand unified theories, or GUTs, in 1973 and 1974. Asymptotic freedom refers to an unexpected phenomenon in certain classes of theories governing particle interactions: the strength of the interaction decreases as the energy of the particles goes up, rather than increasing the way most other forces do. For the first time, particle theorists were able to make accurate and reliable calculations of phenomena such as the strong nuclear force—which keeps quarks bound within nuclear particles such as protons and neutrons—as long as they restricted their calculations to very high energy realms, far beyond anything that had been probed experimentally.

The introduction of GUTs likewise directed attention toward very high energies. Particle physicists realized that the strengths of three of the fundamental forces—electromagnetism and the weak and strong nuclear forces—might converge as particle energies increased. Theorists hypothesized that once the energies rose high enough, the three forces would act as a single undifferentiated force. The energy scale at which this grand unification would set in was literally astronomical: about 10^{24} electron volts, or more than one trillion times higher than the top energies physicists had been able to probe using particle accelerators. GUT-scale energies could never be achieved in Earth-bound laboratories, but some researchers realized that if the entire universe had begun in a hot big bang, then the average energy of particles in the universe would have been extraordinarily high during early periods in cosmic history.

With the advent of asymptotic freedom and GUTs, particle physicists had an obvious reason to begin studying the early universe: the first moments of the big bang would provide them with "the poor man's accelerator," allowing them to observe high-energy interactions that were impossible to re-create on Earth. Scores of scientists, journalists, philosophers and historians have pointed to this development to explain the emergence of particle cosmology.

But is it the whole story? Although the advances in particle theory were certainly important, they are not sufficient to explain the growth of this new subfield. For one thing, the timing is a bit off. Publications on cosmology (worldwide as well as in the U.S.) began a steep rise *before* 1973, and the rate of increase was completely unaffected by the appearance of the papers on asymptotic freedom and GUTs [*see box on opposite page*]. Moreover, GUTs did not receive much attention, even from particle theorists, until the late 1970s and early 1980s. Three of the earliest review articles on the emerging field of particle cosmology, published between 1978 and 1980, ignored asymptotic freedom and GUTs altogether.

New ideas alone were not enough to pave the way for particle cosmology; governmental and educational changes played major roles as well. Until the mid-1960s, U.S. physicists had benefited from a "cold war bubble," a period when the federal government lavished funds on education, defense and scientific research. Beginning in the late 1960s, though, drastic cutbacks triggered by anti–Vietnam War protests, a thawing of the cold war and the introduction of the Mansfield Amendment, which heavily restricted Department of

Beginning in the late 1960s, drastic cutbacks wreaked havoc on physics in the U.S.

Defense spending on basic research, wreaked havoc on physics in the U.S. Nearly all fields of science and engineering went into decline, but physics fell faster and deeper than any other field. The number of new physics Ph.D.s plummeted, falling nearly as fast from 1970 to 1975 as it had risen during the years after Sputnik.

Federal funding for physics also plunged, dropping by more than one third (in constant dollars) between 1967 and 1976. From the 1950s to the mid-1960s, the number of available jobs had always been greater than the number of physics students looking for work at the placement service meetings held by the American Institute of Physics. But employment prospects quickly turned grim: 989 applicants competed for 253 jobs in 1968, and 1,053 students scrambled for 53 positions in 1971.

Particle physics was hardest-hit by far, with federal spending on the field falling by 50 percent between 1970 and 1974. A swift exodus of talent began: between 1968 and 1970, twice as many U.S. researchers left particle physics as entered the field. The number of new Ph.D.s in particle physics fell by 44 percent between 1969 and 1975—the fastest decline of any branch of physics. At the same time, however, the fortunes of astrophysics and gravitation began to rise. Spurred in part by a series of breakthroughs during the mid-1960s, including the discovery of quasars, pulsars and the cosmic microwave background radiation, the number of new Ph.D.s in this area grew by 60 percent between 1968 and 1970 and by another 33 percent between 1971 and 1976—even as the total number of physics Ph.D.s fell sharply.

Surveying the wreckage in 1972, the National Academy's Physics Survey Committee released a new report that highlighted the troubles in particle physics. Many young theorists in that field, the committee noted, were having difficulty switching their research efforts elsewhere because of their "narrow specialization." The report urged the nation's physics departments to revamp how particle theorists were trained: "University groups have a responsibility to expose their most brilliant and able students to the opportunities in all subfields of physics." Changes in university curricula quickly followed, aimed to broaden graduate students' exposure to other areas of physics—including more emphasis on gravitation and cosmology. Across the country, physics programs began to offer new courses on the subject. After ignoring gravitation and cosmology for decades, American publishers pumped out scores of textbooks on the topic to meet the sudden demand.

Inflating the Ranks

THESE ABRUPT CHANGES left their mark on the way physicists viewed concepts such as the Brans-Dicke and Higgs fields. In 1979, after nearly two decades in which virtually no one had even mentioned the two fields in the same paper, let alone considered them to be physi-

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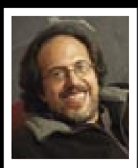
Making the Connection

By the late 1970s a new generation of physicists, conversant with both particle theory and cosmology, explored possible links between Brans-Dicke gravity and the Higgs field.

ANTHONY ZEE

As an undergraduate, Zee worked with gravitation expert John Wheeler at Princeton University, then pursued a Ph.D. in particle theory. He renewed his interest in cosmology while on sabbatical in Paris in 1974.

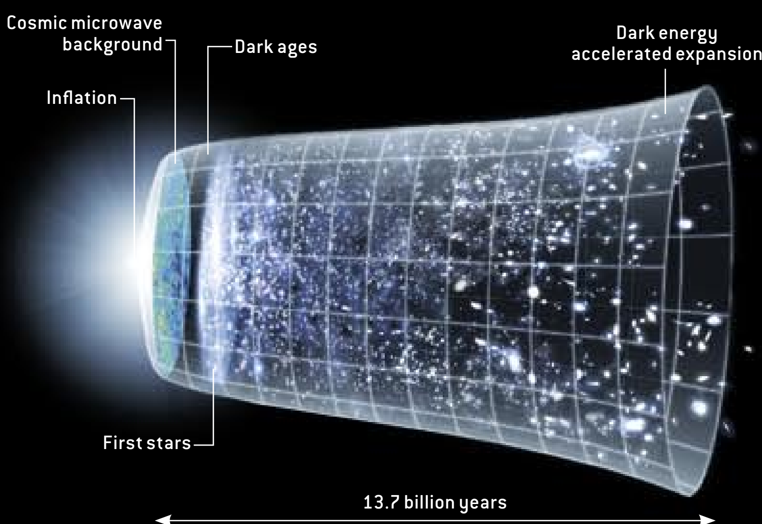


LEE SMOLIN

In the 1970s Smolin studied particle theory and cosmology as a graduate student at Harvard University. He also worked with Stanley Deser of Brandeis University, one of the pioneers of quantum gravity.

ALAN GUTH

Guth earned his Ph.D. in particle physics from the Massachusetts Institute of Technology in 1972. He became interested in cosmology after attending a lecture by Dicke in the late 1970s.



▲ In separate papers published in 1979, Zee and Smolin combined the Brans-Dicke gravitational equations with a Goldstone-Higgs symmetry-breaking potential. In 1981 Guth introduced another field, based on the Higgs, called the inflaton. This field provided the driving force behind a postulated period of superfast expansion—or inflation—during the universe's first moments.

cally similar, two American theorists independently suggested that φ_{BD} and φ_H might be one and the same field. In separate papers, Anthony Zee, then at the University of Pennsylvania, and Lee Smolin, then at Harvard University, glued the two key pieces of φ together by combining the Brans-Dicke gravitational equations with a Goldstone-Higgs symmetry-breaking potential. (Other theorists, working outside the U.S., had tentatively broached similar ideas between 1974 and 1978, but they received little attention at the time.)

In this model, the local strength of gravity initially varied over space and time, with G proportional to $1/\varphi^2$, but its present-day constant value emerged after the φ field settled into a minimum of its symmetry-breaking potential, which presumably occurred in the first moments of the big bang. In this way, Zee and Smolin offered an explanation of why the gravitational force is so weak compared with other forces: when the field settled into its final state, $\varphi = \pm v$, it anchored φ to some large, nonzero value, pushing G (which is inversely proportional to v^2) to a small value.

The career paths of Zee and Smolin illustrate the ways in which physicists focused their attention on cosmology after the collapse of the cold war bubble. Zee had worked with gravitation expert John A. Wheeler as an undergraduate at Princeton in the mid-1960s before pursuing his Ph.D. in particle theory at Harvard. He earned his degree in 1970, at the same time as the biggest declines in that area began. As he later recalled, cosmology had never even been mentioned while he was in graduate school. After postdoctoral work, Zee began teaching at Princeton. He rented an apartment from a French physicist while on sabbatical in Paris in 1974, and in his borrowed quarters he stumbled on a stack of papers by European theorists that tried to use ideas from particle theory to explain various cosmological features (such as why the observable universe contains more matter than antimatter). Although he found the particular ideas in the papers unconvincing, the chance encounter reignited Zee's earlier interest in gravitation. Returning from his sabbatical and back in touch with Wheeler, Zee began to redirect his research interests toward particle cosmology.

Lee Smolin, in contrast, entered graduate school at Harvard in 1975, just as the curricular changes began to take effect. Smolin studied gravitation and cosmology there alongside his course work in particle theory and worked closely with Stanley Deser (based at nearby Brandeis University), who was visiting Harvard's physics department at the time. Deser was one of the few American

NASA/WMAP SCIENCE TEAM (*big bang*); COURTESY OF ANTHONY ZEE (*Zee*); DINA GRASER (*Smolin*); DAVID PARKER *Photo Researchers, Inc.* (*Guth*)

theorists who had taken an interest in quantum gravity in the 1960s, attempting to formulate a description of gravitation that would be compatible with quantum mechanics. He was also the very first physicist to publish an article that cited both the Brans-Dicke work and the Higgs work (although he treated the two fields rather differently and in separate parts of his 1972 paper). Smolin, who worked on topics in quantum gravity, suggested that φ_{BD} and φ_H might be the same field as he was finishing his dissertation in 1979.

Smolin's experiences marked the new routine for his generation of theorists, trained during the mid- to late 1970s. Physicists such as Paul J. Steinhardt, Michael S. Turner and Edward "Rocky" Kolb studied gravitation as well as particle theory in graduate school. Soon Smolin, Turner, Kolb, Steinhardt and others were training their own graduate students to work in the new hybrid area of particle cosmology. For these young theorists and their growing numbers of students, it was natural to associate φ_{BD} and φ_H. Turner, Kolb and Steinhardt each led research groups that pursued further links between φ_{BD} and φ_H during the 1980s.

Building on his 1979 paper, Zee noted in 1980 that standard cosmological theories, such as the big bang model, remained unable to account for the extraordinary smoothness of the observable universe (at least when viewed on the largest scales). Separately, Dicke concluded that the big bang also could not explain the observed flatness of the universe, whose shape could in principle depart quite far from the minimal curvature that astronomers observed. In 1981 Alan H. Guth—then a postdoctoral fellow at Stanford University and now a professor at the Massachusetts Institute of Technology—introduced inflationary cosmology to address both of these problems. At the heart of Guth's model was another scalar field, modeled on the Higgs. Dubbed the inflaton, this field provided the driving force behind a postulated period of superfast expansion—or inflation—during the universe's first moments.

Perhaps today's passionate debates on the direction of theoretical physics are a symptom of the same kinds of growing pains that shook the discipline after the last crash.

Guth's career path was similar to Zee's; he completed his Ph.D. in particle theory at M.I.T. in 1972, before the widespread curricular reforms that brought gravitation back into American classrooms. Hit hard by the collapse of particle physics, Guth toiled in a series of postdoctoral positions for several years. By chance he attended a lecture by Dicke on the flatness problem in the late 1970s, which planted the idea in Guth's head that cosmology might prove interesting for thinking about puzzles in particle theory. While immersed in the new physics of GUTs and working hard to retool himself with some basic background in gravitation and cosmology, he hit on inflation. Most of the physicists who advanced the idea, however, were younger theorists—people such as Steinhardt, Kolb and Turner and their students—who had been pedagogically primed for just such a development. Andrei Linde, then at the Lebedev Physical Institute in Moscow, was likewise poised to explore inflationary ideas: having studied in Russia, where particle physics and gravitation had long flourished side by side, Linde was quick to introduce improvements to the theory.

Since then, it has become routine for particle cosmologists to combine the Brans-Dicke, Higgs and inflaton fields, freely adapting the equations to explain a variety of phenomena. This conceptual leap moved from unthinkable to unnoticeable in only a few academic generations. The shift in attitude illustrates the power of pedagogy and the immense influence that institutional changes can have on scientific thought.

Might history repeat itself? Particle physics was hit hard again in the 1990s (especially with the cancellation of the Superconducting Super Collider, a huge particle accelerator that was under construction in Texas), and funding in the U.S. has continued to slide since then. Perhaps today's passionate debates on the direction of theoretical physics, pitting the advocates of string theory against the proponents of alternative approaches, are a symptom of the same kinds of growing pains that shook the discipline after the last crash.

Physicists are now looking forward to new results from projects scheduled to come online over the next year: the Large Hadron Collider in Switzerland, the Gamma-Ray Large Area Space Telescope and the Planck satellite, which will measure the cosmic microwave background with unprecedented accuracy. With any luck, high-energy physics will emerge just as vibrant and exciting as it did 30 years ago. SA

MORE TO EXPLORE

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