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# *When Fields Collide*

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Particle cosmology is among the hottest of hot topics in physics today. The field investigates the smallest units of matter and their role in determining the shape and fate of the entire universe. In recent years the field has received as much as half a billion dollars from the U.S. Department of Energy, the National Science Foundation, and NASA; it has become a staple topic for popular science writing and NOVA television specials. Almost two new preprints on the topic are posted to the world's central electronic physics preprint server (arXiv.org) *every hour* of every single day.

The field's dramatic success is all the more striking given that it didn't even exist thirty years ago. The rapid rise of particle cosmology illustrates the potent alchemy of ideas and institutions that drives so much of the research enterprise—an entanglement often clearest in hindsight. Exciting new developments within particle theory during the mid-1970s assumed special salience against a backdrop of unprecedented changes that shook the discipline of physics at the time, especially in the United States. These massive changes in educational infrastructure and graduate-student training helped to push certain questions to the research frontier, even as other research programs faltered. In short, particle cosmology emerged, phoenix-like, from one of the most devastating institutional crises modern science has ever seen.

The complex forces at work behind the rise of particle cosmology are thrown into starkest relief by following the fortunes of two sets of ideas: the Brans-Dicke field, introduced by gravitational specialists, and the Higgs field, puzzled over by specialists in particle physics. Neither of these theoretical objects drove the union of particle physics and cosmology. Rather, just like radioactive dyes added to ordinary fluids, they serve as tracers, allowing us to study larger processes. To unpack the early history of particle cosmology, therefore, we must turn to a problem that exercised many physicists during the late 1950s and early 1960s: the problem of mass.

## The Problem of Mass: A Tale of Two $\varphi$'s

During the middle decades of the twentieth century, physicists in at least two branches of the discipline struggled to understand why objects have mass. Mass seems like such an obvious, central property of matter that one might not even think it requires an explanation. Yet finding descriptions of the origin of mass that remained compatible with other ideas from modern physics proved no easy feat. The problem took different forms. Experts on gravitation and cosmology framed the problem in terms of Mach's principle. Mach's principle—named for the physicist and philosopher Ernst Mach (1838-1916), famed critic of Newton and inspiration to the young Einstein—remains stubbornly difficult to formulate, but a good approximation might be phrased this way: are local inertial effects the result of distant gravitational interactions? In other words, does an object's mass—a measure of its resistance to changes in its motion—ultimately derive from that object's gravitational interactions with all the other matter in the universe? If so, do Einstein's gravitational field equations, the governing equations of general relativity, properly reflect this dependence?

Within the much larger community of particle physicists, the problem of mass arose in a different form. Theorists struggled to incorporate masses for elementary particles without violating their equations' required symmetries. Beginning in the 1950s, particle theorists found that they could represent the effects of nuclear forces by imposing special classes of symmetries (invariance under certain gauge transformations) on their equations governing sub-atomic particles' behavior. Yet the terms they would ordinarily include in these equations to represent particles' masses violated these special symmetries. In particular, this impasse affected the force-carrying particles thought to give rise to various nuclear forces. If these particles were truly massless, then the range of nuclear forces should have been infinite—two protons should have been able to exert a nuclear force on each other from across a room, or indeed from across the solar system or galaxy. Such a long range flagrantly contradicted the observed behavior of nuclear forces, which fell off rapidly for distances larger than the size of atomic nuclei. Only if the force-carrying particles had some mass would the nuclear forces' effective range come into line with observations. The origin of mass thus remained no small problem for particle theorists: they could either represent the forces' symmetries but lose all ability to match basic observations, or they could account for the particles' masses but lose all ability to represent the symmetry properties of sub-atomic forces.

Around the same time, physicists in both specialties proposed answers to explain the origin of mass. Both proposals postulated that a new field existed in the universe, whose interactions with all other types of matter explained why we see those objects as possessing mass. On the gravitation side, Princeton graduate student Carl Brans and his thesis advisor, Robert Dicke, pointed out in a 1961 article that in Einstein's general relativity, the strength of gravity was fixed once and for all by Newton's constant, $G$. According to Einstein, $G$ had the same value on earth as it did in the most distant galaxies; its value was the same today as it had been billions of years ago. In place of this, Brans and Dicke suggested that Mach's principle could be satisfied if Newton's constant varied over time and space. To make this variation concrete, they introduced a new field, $\varphi$, inversely proportional to Newton's constant—$G \sim 1/\varphi(x)$—and swapped in $1/\varphi$ for $G$ throughout Einstein's gravitational equations. Now ordinary matter responded both to the curvature of space and time, as in ordinary general relativity, *and* to the variations in the local strength of gravity, coming from $\varphi$. Physically, the main idea behind the Brans-Dicke work was that some new field, $\varphi$, permeated all of space. All matter interacted with $\varphi$, and thus its behavior helped to determine how ordinary matter would move through space and time. Any measurements of an object's mass would therefore depend on the local value of $\varphi$.

Several specialists on particle physics and quantum field theory attacked the problem of mass with a new field at the same time. Yoichiro Nambu, Jeffrey Goldstone, François Englert, Robert Brout, Philip Anderson, T. W. B. Kibble, Peter Higgs and others all focused on the topic during the late 1950s and early 1960s. Their goal: preserving the relevant nuclear-force symmetries while also incorporating massive particles. Building on an analogy to superconducting systems, Jeffrey Goldstone noted in 1961 that equations' solutions need not obey the same symmetries that the equations themselves do. As a simple illustration he introduced a new field, also labeled $\varphi$, whose potential energy density, $V(\varphi)$, behaved as in Figure 1. This potential has two minima, one at a value of $-v$ for the field $\varphi$, and one at the value of $+v$.

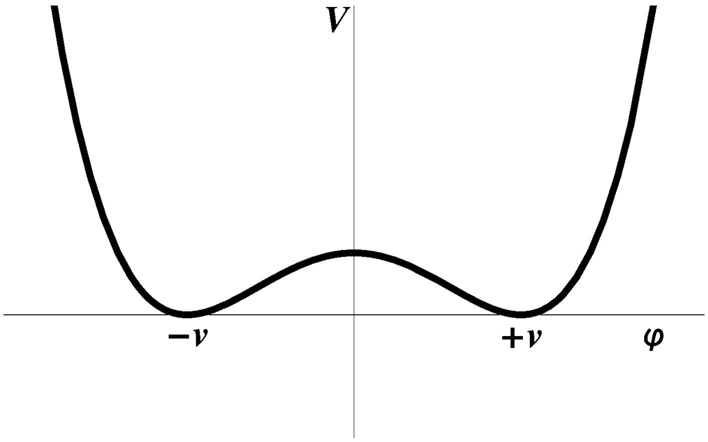

***Figure 1***. Double-well potential, $V(\varphi)$. The energy of the system has a minimum when the field reaches the values $+v$ or $-v$. Although the field's potential energy is symmetric, the field's solution will pick out only one of these two minima, breaking the symmetry of the governing equations.

The energy of the system is lowest at these minima, and hence the field will eventually settle into one of these values. The potential energy is exactly the same—symmetric—for both of these values of the field, even though the field must eventually land at only *one* of these values. The solution to the equations thus spontaneously breaks the equations' symmetry: whereas $V(\varphi)$ is fully left-right symmetric, any given solution for $\varphi$ would be concentrated only on the left or only on the right.

A few years later, in 1964, Scottish theorist Peter Higgs revisited Goldstone's work. Higgs found that when applied to gauge field theories, spontaneous symmetry breaking would yield *massive* particles. The theories would contain interactions between $\varphi$ and all types of particles, including the gauge-field particles that generated nuclear forces. The equations governing these interactions, Higgs demonstrated, obeyed all the requisite symmetries. Before $\varphi$ settled into one of the minima of its potential, these other particles would skip lightly along, merrily unencumbered. Once $\varphi$ arrived at either $+v$ or $-v$, however, the newly anchored $\varphi$ field would exert a drag on anything coupled to it—the sub-atomic equivalent of being mired in molasses. In other words, the force-carrying particles (as well as garden-variety matter like electrons) would behave as if they had a non-zero mass, and any measurements of their mass would depend on the local value of $\varphi$.

Both sets of papers—by Brans and Dicke, and by Higgs—quickly became renowned, acquiring more than 500 citations by 1981; to this day, each of these papers remains within the top 0.1% most-cited physics articles of all time. (See Fig. 2.) Both proposed to explain the origin of mass by introducing a new field, $\varphi$, and accounting for its interactions with all other types of matter. Both were published around the same time, with lengthy articles appearing in the same journal, the *Physical Review*.

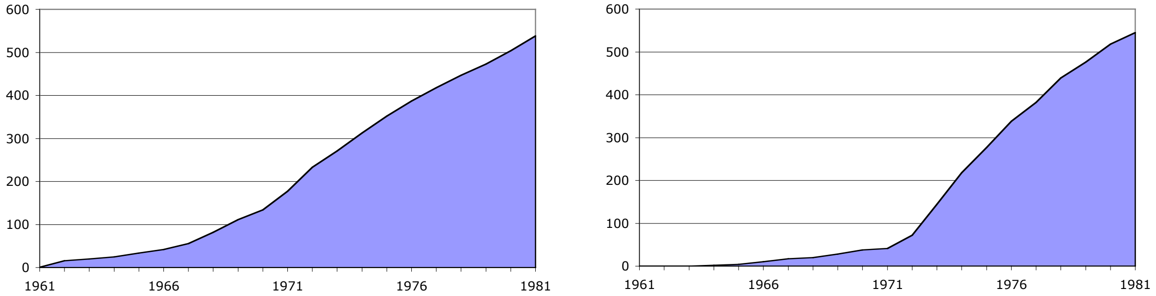

***Figure 2***. Cumulative citations to the Brans-Dicke (left) and Higgs (right) articles, 1961-81. Based on data in *Science Citation Index*.

Given the similarity of their proposals and the quick attention that both received, one might have expected physicists to consider them alongside one another. Yet this almost never happened. The Brans-Dicke field, $\varphi_{BD}$, and the Higgs field, $\varphi_H$, highlight the stark boundaries that existed at the time between the subfields of gravitation and cosmology on the one hand and particle physics on the other. Figure 2 represents 1083 articles that cited either the Brans-Dicke paper or the Higgs papers between 1961 and 1981. Only 6 of these—less than 0.6%—cited *both* Brans-Dicke *and* Higgs, the earliest in 1972 and the rest after 1975. (Although Goldstone's 1961 article received 487 citations between 1961 and 1981, only one paper cited both Brans-Dicke and Goldstone during this period.) Another measure of these communities' separation comes from their author pools: only 21 authors out of the 990 represented in Figure 2 cited both the Brans-Dicke article and Higgs's work—usually in separate papers—between 1961 and 1981.

Clearly the two communities saw different things in their respective $\varphi$'s. To the experts in gravitation and cosmology, $\varphi_{BD}$ was exciting because it offered an alternative to Einstein's general relativity, inspiring renewed theoretical scrutiny of gravitational equations and spurring high-precision experimental tests of gravitation. To the particle theorists, $\varphi_H$ was exciting because it offered hope that gauge field theories might be able to explain the behavior of nuclear forces among massive particles. *Nobody* suggested that $\varphi_{BD}$ and $\varphi_H$ might be physically similar, or even worth considering side by side, before the mid-1970s.

## Pushes, Pulls, and Pedagogy

The divide between particle physics and cosmology was especially sharp in the United States when Brans, Dicke, Goldstone, and Higgs introduced their respective $\varphi$'s. The Physics Survey Committee (PSC) of the U.S. National Academy of Sciences, for example, issued a policy report in 1966 entitled, *Physics: Survey and Outlook*. The committee recommended that both funding and Ph.D.-level personnel for American particle physics be doubled over the next few years—by far the largest increases suggested for any subfield of physics—while calling for virtually no expansion of the already-small areas of gravitation, cosmology, and astrophysics. At a time when some of the most influential Soviet textbooks on gravity began by discussing the latest speculations about nuclear forces, meanwhile, such a blurring of genres remained totally absent from American textbooks.

The U.S. research patterns—so starkly laid out in the 1960s policy reports, and mirrored in the separate treatments of $\varphi_{BD}$ and $\varphi_H$—were not set in stone. Indeed, by the late 1970s the separation between cosmology and particle physics no longer seemed quite so extreme. Looking back on the rapid rise of particle cosmology, physicists almost always point to two important developments that spurred the merger. Both concerned changes in particle theory during the mid-1970s: the discovery of "asymptotic freedom" in 1973, and the construction of the first "grand unified theories," or GUTs, in 1973-74.

Asymptotic freedom refers to an unexpected phenomenon within certain classes of gauge field theories: 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 such phenomena as the strong nuclear force—the force that 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. (H. David Politzer, David Gross, and Frank Wilczek shared the 2004 Nobel Prize in Physics for their discovery of asymptotic freedom.)

The introduction of GUTs likewise pointed particle theorists' attention toward very high energies. Some particle theorists realized that the strengths of three of the basic physical forces—electromagnetism, the weak nuclear force (responsible for such phenomena as radioactive decay), and the strong nuclear force—might become equal at some very high energy. (See Fig. 3.) Theorists hypothesized that above that energy scale the three forces would act as a single undifferentiated force, subject to a particular gauge symmetry group. Below that energy scale, the GUT symmetry would be spontaneously broken, leaving three distinct gauge groups, each with its characteristic interaction strength.

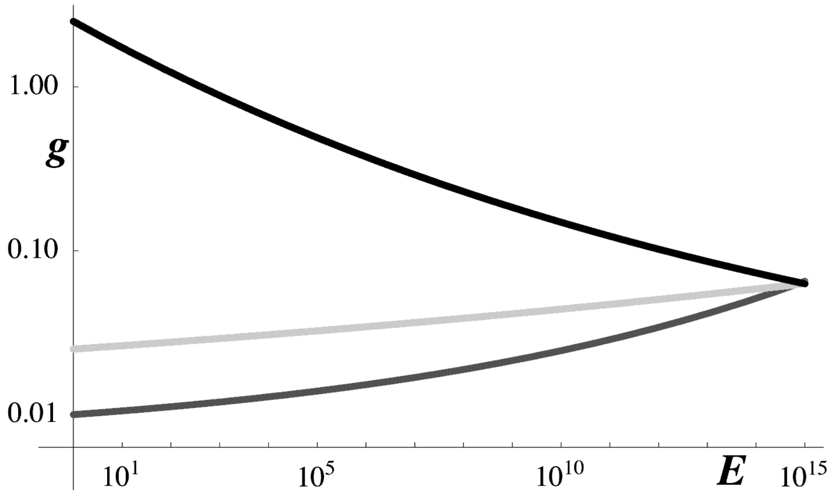

***Figure 3***. Interaction strength ($g$, in arbitrary units) versus energy ($E$, in billions of electron-volts). From top to bottom: the interaction strengths associated with the gauge groups representing the strong nuclear force, the weak nuclear force, and electromagnetism. Note that the strength of the strong nuclear force decreases with increasing energy ("asymptotic freedom"), while those of the weak and electromagnetic forces increase with energy, allowing all three interaction strengths to intersect in the vicinity of $10^{15}$ billion electron-volts.

The energy scale at which "grand unification" might set in was literally astronomical: more than one trillion times higher than anything particle physicists had been able to probe using earth-bound particle accelerators. Physicists had no possible way of accessing such energy scales via their traditional route; even with three decades of improvements in the underlying technology, today's most powerful particle accelerators have increased the energies under study by about a factor of one hundred, a far cry from one trillion. So GUT-scale energies could never be created in physicists' laboratories. But some began to realize 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 at early times in cosmic history, cooling over time as the universe expanded. With the advent of asymptotic freedom and GUTs, particle physicists therefore had a "natural" reason to begin asking about the high-energy early universe: cosmology would provide "the poor man's accelerator." Scores of physicists, journalists, philosophers, and historians have repeated this refrain to explain the emergence of particle cosmology: key ideas within particle theory drove particle theorists to think about cosmology, beginning in the mid-1970s, and—presto chango—the new subfield was born.

Is this the whole story? Although certainly important, these changes in particle theory are not sufficient to explain the growth of the new subfield. For one thing, the timing is a bit off. Publications on cosmology (worldwide as well as in the United States) began a steep rise *before* 1973-74, and the rate of increase was completely unaffected by the appearance of the papers on asymptotic freedom and GUTs. (See Fig. 4.)

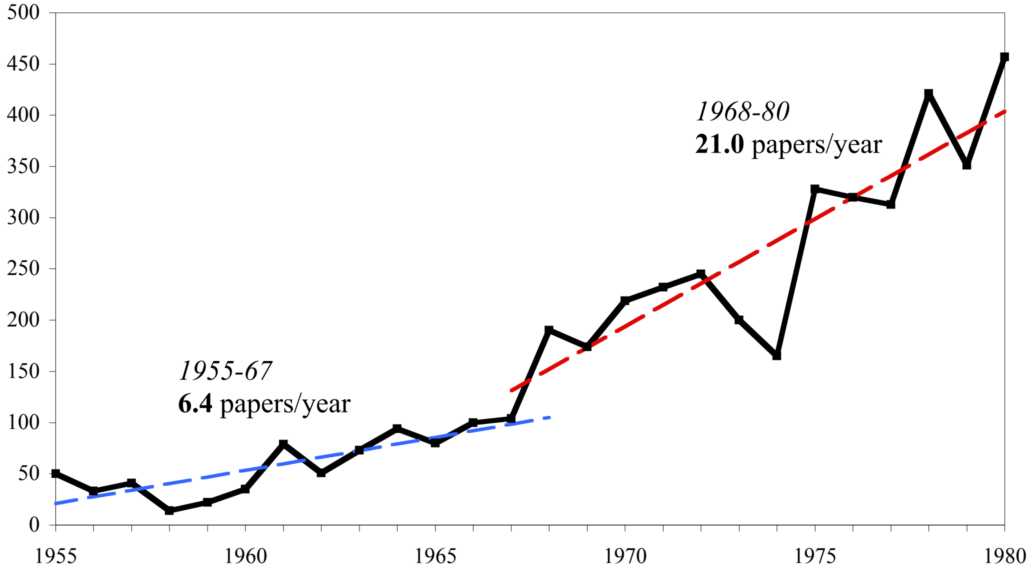

***Figure 4***. Number of papers published worldwide on cosmology per year. Dashed lines show average rates of growth during the two periods. Based on data in *Physics Abstracts*. Within the main American research journal, the *Physical Review*, the rate at which cosmology articles appeared similarly quadrupled between the periods 1960-67 and 1968-73.

Moreover, although GUTs were introduced in 1973-74, they 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, highlighting other work instead, some of it dating back to 1972, before either asymptotic freedom or GUTs had even been introduced.

More than just ideas were at stake in the creation of particle cosmology. Institutions and infrastructure played major roles as well. Détente, major cutbacks in education and defense spending, anti-Vietnam War protests, and the Mansfield Amendment (which heavily restricted Defense Department spending on basic scientific research) wreaked havoc on physics in the United States beginning in the late 1960s. Nearly all fields of science and engineering entered a period of decline; yet physics fell faster and deeper than any other field. The first "Cold War bubble"—akin to a speculative stock-market bubble, which had seen physicists funded and admired like no other period in American history—burst suddenly, and physicists in the United States quickly began to talk of the crisis facing their discipline. The overall number of physics Ph.D.s granted per year in the United States plummeted, falling nearly as fast during 1970-75 as it had risen during the years after Sputnik. (See Fig. 5.)

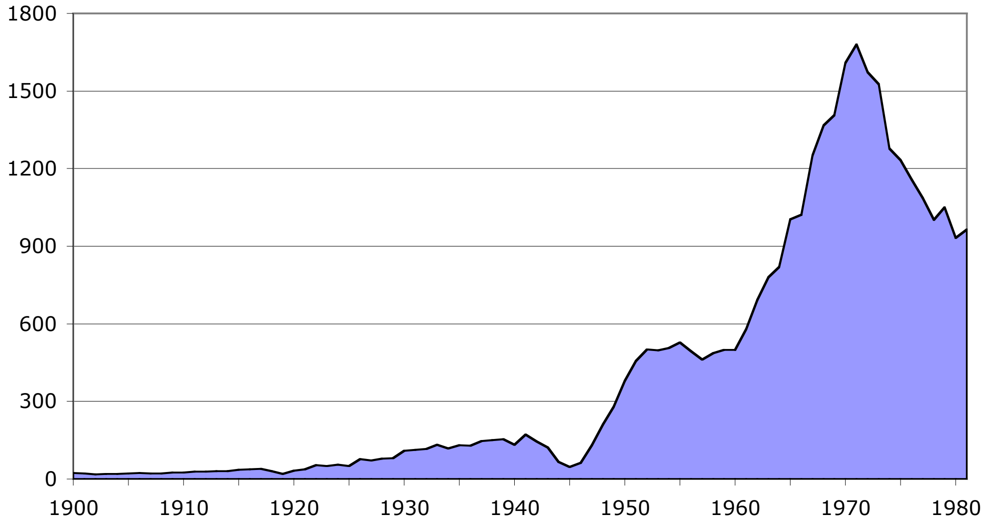

***Figure 5***. Number of physics Ph.D.s granted per year in the United States, 1900-81.

Federal funds for physics likewise fell rapidly, down by more than one-third between 1967 and 1976 (in constant dollars). Whereas employers had always outnumbered physics students looking for jobs at the American Institute of Physics's placement service meetings from the 1950s through the mid-1960s, employment prospects quickly turned grim for young physicists in the United States: 989 applicants competed for 253 jobs in 1968, while 1,053 sought out only 53 jobs on offer in 1971. By the early 1970s, physicists in the United States faced the worst crisis their discipline had ever seen.

The cuts did not fall evenly across the discipline. Hardest hit by far was particle physics. Federal spending on particle physics fell by 50% between 1970 and 1974 (a combination of direct cut-backs and inflation), combined with a sudden drop in government demand for high-energy physicists. A rapid out-flow of particle physicists began: between 1968 and 1970 alone, twice as many physicists left particle physics as entered it in the United States. The downward slide continued into the 1970s: the number of new particle physics Ph.D.s trained per year in the United States fell by 44% between 1969 and 1975—the fastest decline of any subfield. As particle physicists' fortunes tumbled, meanwhile, astrophysics and gravitation became one of the fastest-growing fields in American physics. Spurred in part by a series of new discoveries during the mid-1960s (such as quasars, pulsars, and the cosmic microwave background radiation), as well as by innovations in experimental design, the number of new Ph.D.s in this area per year grew by 60% between 1968 and 1970, and by another 33% between 1971 and 1976—even as the total number of physics Ph.D.s fell sharply.

Surveying the wreckage a few years into the slump, the Physics Survey Committee (PSC) released a new report, *Physics in Perspective* (1972). The committee noted that theoretical particle physicists had fared worst of all when the cut-backs hit. When demand for particle physicists fell off, too many of the young particle theorists had difficulty switching their research efforts elsewhere because of their "narrow specialization." The nation's physics departments needed to revamp how particle theorists were trained, urged the PSC: "University groups have a responsibility to expose their most brilliant and able students to the opportunities in all subfields of physics." Particle theorists were the only subfield singled out for such criticism in the PSC's 2500-page report. Curricular changes quickly followed, aimed to broaden graduate students' exposure to other areas of physics—including more emphasis on gravitation and cosmology. Across the country, physics departments began to offer new courses on the subject. American publishers pumped out scores of new textbooks on gravitation and cosmology—having all but ignored the topic for decades—to meet the sudden demand.

These massive changes in American physics left their mark on the way theorists handled such theoretical objects as $\varphi_{BD}$ and $\varphi_H$. In 1979, two American theorists independently suggested that $\varphi_{BD}$ and $\varphi_H$ might be one and the same field—this 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 physically similar. Anthony Zee and Lee Smolin separately introduced a "broken-symmetric theory of gravity" by combining the Brans-Dicke gravitational equations with a Goldstone-Higgs symmetry-breaking potential, in effect gluing the two key pieces of $\varphi$ together. (Similar ideas had been broached tentatively by theorists in Tokyo, Kiev, Brussels, and Bern between 1974 and 1978, though they received very little attention at the time.) In this model the local strength of gravity, governed by Newton's "constant," $G \sim 1/\varphi^2$, not only could vary over space and time (as in the Brans-Dicke work); its present-day value emerged only after the field, $\varphi$, settled into a minimum of its symmetry-breaking potential, just as in the Higgs work. In this way, Zee and Smolin could try to explain why the gravitational force is so weak, compared to other forces: when the field settles into its final state, $\varphi = \pm v$, it anchors $\varphi$ to some large, non-zero value, pushing $G \sim 1/v^2$ to a small value.

Anthony Zee's path to uniting the two $\varphi$'s illustrates one way in which theorists in the United States wandered into cosmology from particle theory after the collapse of the Cold War bubble. He had worked with gravitation-expert John Wheeler as an undergraduate at Princeton in the mid-1960s before pursuing his Ph.D. in particle theory at Harvard, earning his degree in 1970 just 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 swapped apartments with a French physicist while on sabbatical in Paris in 1974, and in his borrowed quarters he stumbled upon a stack of papers by European theorists that tried to use ideas from particle theory to explain various cosmological features (such as why our 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 more and more toward particle cosmology.

Lee Smolin, on the other hand, entered graduate school at Harvard in 1975, just as the curricular changes began to take effect. Unlike Zee, Smolin formally studied gravitation and cosmology as a graduate student alongside his coursework in particle theory—he didn't need to stumble into one area from the other. Smolin worked closely with Stanley Deser (based at nearby Brandeis University), who was visiting Harvard's department at the time. Deser was one of very few American theorists who had taken an interest in quantum gravity by the 1960s—attempting to formulate a description of gravitation that would be compatible with quantum mechanics. He was also the very first physicist in the entire world 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's other main advisor was Sidney Coleman, a particle theorist who just a few years earlier had begun teaching the first course on general relativity to be offered in Harvard's physics department for nearly twenty years. He completed coursework with Steven Weinberg, whose influential textbook, *Gravitation and Cosmology* (1972), had recently appeared. Meanwhile, Smolin also took intense courses on gauge field theory and GUTs with several architects of the new material, including Howard Georgi and visiting professor Gerard 't Hooft. Building on this curricular preparation, Smolin worked on topics in quantum gravity, and suggested that $\varphi_{BD}$ and $\varphi_H$ might be one and the same field just as he was finishing his dissertation in 1979.

Smolin's experiences marked the new routine for his generation of theorists, trained during the mid- and late-1970s to work at the interface of gravitation and particle theory. Theorists like Paul Steinhardt, Michael Turner, Edward "Rocky" Kolb and others—each of whom, like Smolin, received his Ph.D. between 1978 and 1979—

devoted formal study to gravitation as well as to 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. For these young theorists and their growing numbers of students, it became "natural" to associate $\varphi_{BD}$ and $\varphi_H$. Turner, Kolb, and Steinhardt each led groups that pursued further links between $\varphi_{BD}$ and $\varphi_H$ during the 1980s, constructing cosmological models in which $\varphi_{BD}$ and $\varphi_H$ either appeared side-by-side or were identified as one single field.

## Inflating the Ranks

Building upon his 1979 paper uniting $\varphi_{BD}$ and $\varphi_H$, Anthony 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 supergalactic scales). Separately, Robert Dicke concluded that the big bang likewise remained handicapped to explain the observed flatness of our universe, whose shape (according to both Einstein's general relativity and the Brans-Dicke model) could in principle depart quite far from the minimal curvature that astronomers routinely observed. Alan Guth introduced inflationary cosmology in 1981 in response to both of these conundra. At the heart of Guth's model lay a new field, the inflaton, the postulated driving force behind a period of superfast exponential expansion—or inflation—during the earliest history of our observable universe. Since its introduction, the inflaton has become the "poster child" of fields at the heart of particle cosmology.

Guth's path to inflation mirrored Zee's path to particle cosmology more generally. He completed his Ph.D. in particle theory at M.I.T. in 1972, before both the introduction of asymptotic freedom and the widespread curricular reforms that brought gravitation back into American classrooms. Hit hard by the collapse of particle physics in the United States, 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 slowly planted the idea in Guth's head that cosmology might prove interesting for thinking about particle theory puzzles. While immersed in the new physics of GUTs, and working hard to re-tool himself with some basic background in gravitation and cosmology, he hit upon inflation.

Among the earliest to pick up and run with the idea, however, were younger theorists—people like Steinhardt, Kolb, Turner, and their students—who had been pedagogically well-primed for just such a development. Andrei Linde was likewise poised to push inflationary ideas farther and faster than ever before. Having grown up in the thriving Moscow tradition in which particle theory and gravitation had flourished side-by-side, Linde immediately began introducing entire new inflationary schemes and major improvements to the framework as a whole. Like the U.S.-trained physicists of his generation, it had already become second nature for Linde and his peers to study the dynamics of such fields from both particle theory and gravitational perspectives.

Since that time, theoretical objects like the Brans-Dicke, Higgs, and inflaton fields have become staples of everyday life in the bustling field of particle cosmology. One can scarcely avoid them. Whether working on quantum-gravitational corrections to Einstein's equations, low-energy predictions from superstring theory, early-universe alterations to gravity during an inflationary epoch, or possible sources of the "dark energy" that has thrust our universe into a mini-inflationary phase today, these types of fields are simply everywhere. Physicists now routinely combine them into a single field, hardly thinking twice about a move that was so novel a few decades ago. Indeed, from today's vantagepoint, it seems downright bizarre that for so long after their introduction, physicists never considered the Higgs and Brans-Dicke fields in the light of one another. The fields' union has moved from unthinkable to unnoticeable in just a few academic generations.

This seeming naturalness—the banality of combining these fields today, or the bizarreness of holding them at arm's length—illustrates the power of pedagogy. Vast institutional changes shook the discipline of physics, especially in the United States, during the late 1960s and early 1970s. These major changes in institutions and infrastructure led in turn to concrete changes in training, re-shaping the boundaries of what young physicists would find natural, compelling, or worth pursuing. Emerging from physics's darkest hour, a new specialty was born.

## *For Further Reading*

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