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SIDNEY COLEMAN
1937–2007

A Biographical Memoir by

HOWARD GEORGI

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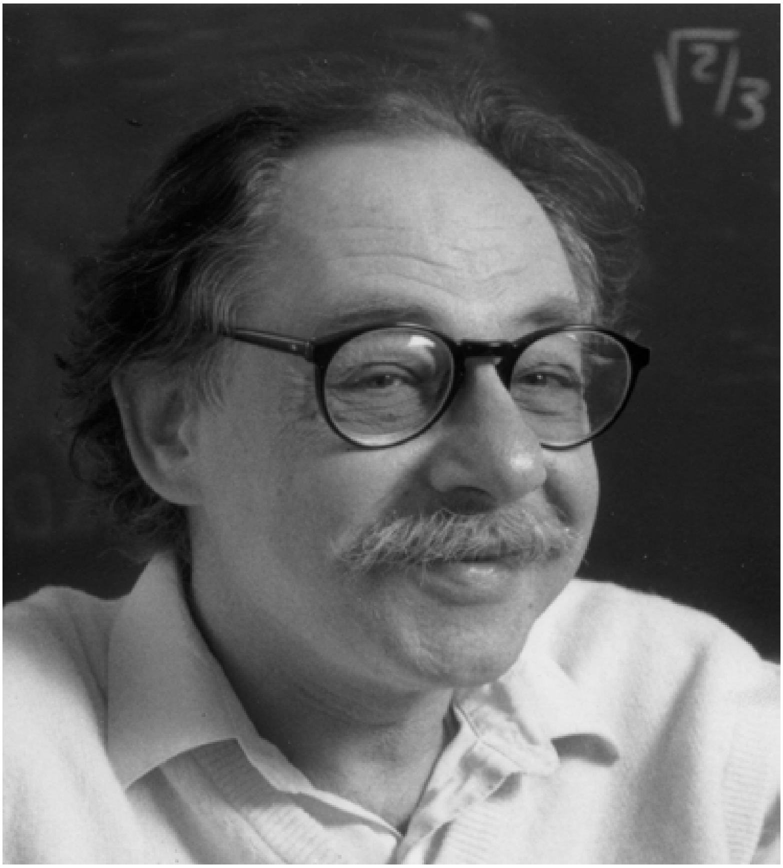
Biographical Memoir



S Coleman

SIDNEY COLEMAN

March 7, 1937-November 18, 2007

BY HOWARD GEORGI

SIDNEY COLEMAN BEGAN HIS Ph.D. thesis (1962) with a quotation from *Justine* by the Marquis de Sade: "What we do here is nothing to what we dream of doing." Coleman's brilliant career as one of the leading quantum field theorists in the world probably surpassed even his graduate student dreams. He was an indispensible player in the resurgence of quantum field theory in the 1960s and 1970s, and indeed he taught particle physicists, established and aspiring, a new way of thinking about quantum field theory. There is a telling and audacious short paragraph early in his thesis.

> To step out from behind the first person plural for a moment, I like to think of this [first] part of the work as a calculation—not strikingly different in spirit from a calculation of a radiative correction. It is true that the first half of this thesis does not look like the usual physics calculation, but that is only because the computational tools are algebraic rather than analytic.

Symmetry had been an important tool in physics from the beginning. But already as a graduate student Coleman understood that he was bringing to the forefront a set of algebraic techniques in group representation theory that had usually played a secondary role to analysis in theoretical particle physics. The important objects were not the symmetry transformations themselves but their "generators"—associated with infinitesimal transformations. The mathematical tools were well known to physicists for the simplest compact Lie algebras because of the connection with angular momentum operators, the generators of rotations. For more complicated symmetries they were not part of the standard theoretical physics toolbox.[1] Coleman loved symmetry and quantum field theory. He understood the amazing power of these algebraic tools in working with quantum field theory. He knew that he had to explain them carefully to his elders (and eventually to his students). And he knew that he had the requisite skills to do it.

Sidney Coleman was born in Chicago on March 7, 1937. His father, a businessman, died when he was nine, and the family lived through hard times in the far North Side of Chicago. His brother, Robert L. Coleman, says[2] that in the 1940s Sidney became interested in the building of the atomic bomb and declared his ambition to become a physicist. In high school he and a friend built a primitive computer and won the Chicago Science Fair.

He graduated from the Illinois Institute of Technology in 1957 and went on to graduate school at Caltech, where he studied with Murray Gell-Mann and collaborated with Sheldon Glashow. In 1961 Coleman came to Harvard as the Corning Lecturer and Fellow. For over 30 years he was the magisterial leader of the Harvard group in particle theory. He was a legendary character as well as a leading theorist. I learned group theory from Coleman when I was an undergraduate at Harvard in the mid 1960s, and it was he who phoned me in 1971 after my four years away in graduate school to offer me a postdoctoral position at Harvard, a call I will never forget. In this memoir, whenever possible, I have let him speak for himself, because he did it so well in his writing.

A remarkably clear thinker, a polymath, and a natural expositor and pedagogue, Coleman was usually not the first to come up with a new approach to a phenomenological puzzle; but he was always among the first to understand new theoretical ideas, often much more clearly than the inventors themselves. He was often the first to put new theoretical ideas on a firm footing and to understand their connection with deep issues in the foundations of physics. And he frequently took the lead in explaining them clearly to the community. As his Nobel Prize-winning colleague Steven Weinberg said, "Sidney was most interested in understanding the foundations of theory rather than the special cases relevant to describing nature, and he revealed many of the deepest aspects of this grand theoretical structure through his work." Many of Coleman's best-known contributions take the shape of theorems, or equivalence relations: the Coleman-Norton theorem (Coleman and Norton, 1965); the Coleman-Mandula theorem (Coleman and Mandula, 1967); "The Invariance of the vacuum is the invariance of the world" (Coleman, 1966); "There are no Goldstone bosons in two-dimensions" (Coleman, 1973); "Quantum sine-Gordon equation as the massive thirring model" (Coleman, 1975), and many more.

Coleman's approach to particle theory is well illustrated in the sequel to the story of higher approximate symmetries discussed in his thesis. Coleman's many clear papers and lectures (some explicitly pedagogical with names like "Fun with SU(3)") played a crucial role in making Gell-Mann's discovery of the eight-fold way (Gell-Mann, 1961; Ne'eman, 1961) accessible to the quantum field theory community. For many quantum field theorists the 1960s became the decade of higher symmetries. Many important contributions came out of this, perhaps most notably the structure of what we now know as the standard model. As often happens when theorists are given new toys to play with, many got carried away and took the ideas too far in the wrong directions:

approximate symmetries combining Gell-Mann's SU(3) with symmetries of space and time. Coleman dealt with this by proving a theorem. The Coleman-Mandula theorem "on the impossibility of combining space-time and internal symmetries in any but a trivial way" put much needed brakes on a runaway idea.

The Coleman-Mandula theorem is also an illustration of an issue that a number of Coleman's colleagues experienced. Sometimes Coleman knew too much. There is an important loophole in the Coleman-Mandula theorem. It did not apply to supersymmetry because they did not consider the possibility of anticommuting parameters. Thinking in terms of theorems may lead you astray if your assumptions are not appropriate. Coleman knew so much that while it could be very valuable to consult with him about a nascent idea, it could also be discouraging. Sometimes, in order to make progress, one has to ignore (or be ignorant of) the known reasons why something doesn't work. Coleman knew them all, and his colleagues had to learn to use his immense knowledge without being too intimidated or discouraged from trying crazy ideas.

When Coleman wrote his thesis, it was not obvious what would be the most important application of higher symmetry in quantum field theory to particle physics. Gell-Mann's approximate SU(3), the subject of Coleman's thesis, we now think of as an accidental by-product of the fundamental theory of the strong interaction, arising because the values of some parameters (the *u*, *d*, and *s* quark masses) are small (for reasons that we still do not understand). Much more important is that the dynamics of the strong interactions and of the weak and electromagnetic interactions as well all involve symmetry in an essential way. A crucial step had come long before with Yang and Mills (1954) and Utiyama (1956) who wrote down theories with gauge symmetry in which the symmetry was tied to the fundamental interactions. These were extensions of quantum electrodynamics to incorporate non-Abelian symmetry. This was a time bomb. These theories were mathematically fascinating and seemed somehow important physically, but nobody quite knew what to make of them when they were first written down, in part because they seemed to require massless particles that were not seen in the world. Even after Peter Higgs and others showed how to hide the symmetries and eliminate the massless particles by spontaneously breaking the gauge symmetry, and Weinberg, combining this with the symmetry structures suggested by Glashow and Salam and Ward had written down what would turn out to be the right theory of the weak interactions, the fundamental problem remained. No one quite knew what these theories meant. When Gerard 't Hooft (1971a,b); 't Hooft and Martinus Veltman (1972); and others finally figured this out in the early 1970s, the floodgates opened because quantum field theorists had a huge new world of theories that they suddenly had the tools to explore. At the same time, experimental particle physicists were pushing their machines beyond the 1 GeV energy scale and beginning to see evidence of new and surprising physics at (what we then thought of as) high energy. The next few years were a remarkable confluence of theoretical and experimental progress in particle physics.

While Coleman's contributions to the enormous progress made in particle theory in the 1970s were huge, he was not directly involved in interpreting the exciting experimental results. Indeed, it was characteristic of Coleman that many of his deepest and most important contributions are hidden in long papers that might seem to the casual observer to be purely technical, working out of some minor mathematical detail. Two wonderful examples of this from the 1970s are the papers "Radiative Corrections as the Origin of Spontaneous Symmetry Breaking" (Coleman and Weinberg, 1973) and "Quantum sine-Gordon Equation as the Massive Thirring Model" (Coleman, 1975). In the first of these Coleman and his student Erick Weinberg solve a puzzle. They begin thus,

> Massless scalar electrodynamics, the theory of the electromagnetic interactions of a mass-zero charged scalar field, has had a bad name for a long time now; the attempt to interpret this theory consistently has led to endless paradoxes. In this paper we describe how nature avoids these paradoxes: Massless scalar electrodynamics does not remain massless, nor does it remain electrodynamics.

In fact, this paper was much more than a consistent account of a pathological theory. It was enormously influential as a handbook for dealing with scale violation in quantum field theory. Coleman had been thinking hard about scale invariance since the late 1960s. In this paper, written soon after the revolution of spontaneously broken non-Abelian gauge theories, Coleman pulled together all the most useful techniques and described them with his characteristic clarity. In the process he discovered an important and very general phenomenon.

> The surprising thing is that we have traded a dimensionless parameter, α, on which physical quantities can depend in a complicated way, for a dimensional one…on which physical quantities must depend in a trivial way, governed by dimensional analysis. We call this phenomenon dimensional transmutation."

We now know that dimensional transmutation is responsible for many of the surprising features of the strong interactions at high energies that were appearing in experiments when this paper was written.

Coleman's student, David Politzer, collaborated with Coleman and Erick Weinberg on some parts of the Radiative Corrections paper, and it was in this process that Politzer became interested in calculating the scaling properties of a non-Abelian gauge theory with no scalars. This led Politzer to the discovery of asymptotic freedom, also found at Princeton by David Gross and Frank Wilczek, for which the trio were awarded the 2004 Nobel Prize.[3] Asymptotic freedom and dimensional transmutation, along with quark confinement, are the three dynamical pillars of QCD—our theory of the strong interactions based on the non-Abelian gauge theory SU(3). This theory incorporates and explains Gell-Mann's approximate SU(3) symmetry that was the subject of Coleman's thesis (Fritzsch et al., 1973; Weinberg, 1973), and as developed by Politzer and others, it led to the QCD parton model that now allows us to interpret the results of high-energy experiments with protons in terms of the fundamental physics of the quarks and gluons inside.

In "Quantum sine-Gordon equation as the massive thirring model" Coleman (1975) studied a pair of quantum field theories in one space and one time dimension. Neither of these theories is particularly important in itself (and certainly not very relevant to our world with three space dimensions). But in a masterful (and as usual exquisitely documented) analysis Coleman identified a precise equivalence between the two. He says,

> Thus, I am led to conjecture a form of duality…for this two-dimensional theory. A single theory has two equally valid descriptions in terms of Lagrangian field theory: the massive Thirring model and the quantum sine-Gordon equation. The particles which are fundamental in one description are composite in the other:…Speculation on extending these ideas to four dimensions is left as an exercise for the reader.

This concept of duality—that seemingly totally different classical theories can nonetheless describe exactly the same physics at the quantum level—became a central theme in the superstring revolution of the mid 1990s and continues to be central in field theory and string theory to this day.

In the late 1970s and 1980s the results and the techniques in Coleman's work on vacuum decay were crucial for the beginnings of the quantitative description of the beginning of the universe. He also addressed one of the deepest puzzles in physics in "Why there is nothing rather than something: A theory of the cosmological constant" (Coleman, 1988a). Here he argued that quantum gravity makes the value of the cosmological constant a quantum variable rather than a parameter, so that in his words, "The predictive power of the theory of everything has gone down the wormhole." He further argued that a zero constant was much more likely than any other value, though he acknowledged that

> the Euclidean formulation of gravity is not a subject with firm foundations and clear rules of procedure; indeed, it is more like a trackless swamp. I think I have threaded my way through it safely, but it is always possible that unknown to myself I am up to my neck in quicksand and sinking fast.

In this case he may well have been in quicksand, but his approach set the stage (for better or worse) for probabilistic approaches to the puzzle.

For much of his career Coleman was the preeminent teacher of quantum field theory in the world and his approach to the subject, relying heavily on beautiful symmetry arguments, had enormous influence. He had 40 Ph.D. students, many of whom became leaders in high-energy theory and other areas of physics. Many hundreds of students from all over the Boston area attended his superbly organized and witty lectures on quantum field theory, and his notes formed the basis of courses and eventually textbooks used worldwide. Students and colleagues pored over his classic papers and summer school lectures. These were masterpieces. Coleman labored over them until no word was out of place and no explanatory or pedagogical opportunity was missed. Andrew Cohen tells the following personal story:

> [It] happened when I was a beginning grad student while we were working on the Evaporation of Q-balls [Cohen et al., 1986]. Aneesh [Manohar] (who was my roommate at the time) was worried that Sidney's exacting writing standards would mean that the paper would take forever to write. I suggested we go talk to Sidney and try to get him started early on the writing. When we went into Sidney's office Aneesh blurts out "Andy has volunteered to write a draft of the introduction." After Sidney gave me the evil eye for a moment he (seemingly reluctantly) agreed. I was terrified. I eventually went to Sidney's previous paper where he introduced the notion of Q-balls, and through cutting and pasting managed to produce most of a coherent introduction, using essentially Sidney's own words. The next morning I slipped it under his door and waited for him to come in. Sometime in the middle of the afternoon Sidney comes to find me and says "I was worried about having you work on the introduction, but this writing is fantastic!"

Many of Coleman's lectures were collected in his book *Aspects of Symmetry* (Coleman, 1988b). In 1989 he received the Award for Scientific Reviewing from the National Academy of Sciences for his "lucid, insightful, and influential reviews."

While his first love was the teaching of graduate-level quantum field theory, Coleman also gave brilliant undergraduate lectures. This was a personal sacrifice, because Coleman was renowned for doing his best work in the wee hours of the morning, and it was never clear whether he was better off getting a few hours of sleep before a late morning undergraduate class, or simply staying up for it.

Fortunately, some of his lectures survive and are collected on the Harvard Physics Department Web page.[4] Perhaps the most famous is "Quantum mechanics in your face" given at the New England sectional meeting of the American Physical Society (Apr. 9, 1994) in which Coleman pokes very educational fun at the concept of the reduction of the wave packet. The talk contains a great selection of Coleman jokes. For example, explaining that the talk is pedagogical and that nothing in it is original, he says, "I claim some responsibility but no credit—the reverse of the usual scholarly procedure."

But he goes on to explain clearly with just first-year quantum mechanics that there is no problem with the interpretation of quantum mechanics. "The problem is the interpretation of classical mechanics."

Not a cloistered academic, Coleman was a public intellectual in the best sense. He served behind the scenes as a science adviser to a number of movies and NOVA programs. He had a deep and lifelong interest in science fiction and wrote and published science fiction criticism himself. As a teenage college student he was one of the cofounders of Advent Publishers, which is devoted to science fiction criticism.

Coleman's friend and cofounder of Advent, Earl Kemp, collected many Coleman memories for his online efanzine *eI*, in an issue[5] devoted to Sidney Coleman and Kurt Vonnegut. Many of these are Coleman stories that Coleman loved to tell himself. Robert Lichtman writes,

> I also wish I could locate a copy of Sidney's account of the first time he was a Visiting Lecturer at Cambridge (or possibly Oxford). After dinner in the Commons, a silver snuff-box was, as per Tradition, passed from hand to hand. Being Sidney, he opened it and took a pinch. Anyone who knows him can visualize his slow smile when one of the Dons informed him that he was the first person to do that in more than a hundred years. If memory serves, he noted that it was fresh snuff, and mentioned that "of course one expects an old British University to pay attention to such details."

Robert Silverberg writes,

> While traveling—alone—in France in the early 1970s, Sidney unexpectedly contracted a case of what turned out to be crabs. "Unexpectedly" because this is customarily a venereal disease, and he had been a model of chastity throughout his trip. The offending organisms must have been concealed in the bedding of his hotel room, he decided, and so he had suffered a case of punishment without the crime. But during the trip he had not, however, remained true to the dietary restrictions imposed by the religious doctrines of his forefathers; and, he said, after visiting a French doctor and having his ailment diagnosed for what it was, he was granted a vision of

his Orthodox grandfather rising up in wrath before him and thundering, "Thou hast eaten crustaceans, child, and now thou shalt be devoured by crustaceans thyself!"

Though Coleman's involvement with Advent wound down and he eventually retired in 2001, it is remarkable that he was still writing serious science fiction criticism while he was transforming particle theory in the 1970s. Here is a snippet from a review in 1974, reprinted in a moving website put together as a memorial by his science fiction colleagues.[6]

I do not know why Zelazny began this process of reverse alchemy five years ago, why he put away his magician's tricks and turned his gold into lead. Maybe he simply ran out of steam; it happens often enough in literary careers; being a genius is a profession for the young. Or it might have been the pressures of the market. Zelazny began free-lancing full time about five years ago, and the economics of sf writing are not such as to allow time for tinkering with the elaborate and delicate machineries of wit. I don't know why; all I know is that we once had something unique and wonderful, and it is gone.

Coleman was an accomplished amateur magician in his teenage years.

Coleman received many awards: the Boris Pregel Award from the New York Academy of Sciences; the Award for Lectures in Physics, Centro Ettore Majorana (International School of Physics, Erice); the Dirac Medal from the International Centre for Theoretical Physics; and the Dannie Heineman Prize from the American Physical Society. He was a fellow of the American Physical Society, the American Academy of Arts and Sciences, and was elected to membership in the National Academy of Sciences in 1980.

Coleman's wit could be as biting as it was clever, and his friends bore the brunt of this and loved it. They could count on him to keep their head sizes under control. "Courtesy," Coleman argued, "is for strangers. Kindness is for friends." Health problems bedeviled the end of Coleman's life and deprived the world of what would surely have been an affectionately irreverent elder statesmanship. In the words of Sheldon Glashow, one of Coleman's best friends throughout his adult life, and in a scientific association of almost 40 years Coleman's first and last collaborator on theoretical particle physics (Coleman and Glashow, 1961, 1962, 1964,1997, 1998, 1999; Coleman et al., 1964, 1966): "Sidney was both an incomparable teacher and the most learned sage and sharpest critic in the world of theoretical physics: He was Pauli's tongue in Einstein's image. We have been deprived all too soon of one of our generation's most profound and imaginative minds."

Sidney Coleman is survived by his wife of 25 years, Diana Coleman of Cambridge, Massachusetts; and his brother, Robert Coleman of Albany, California; and many friends and admirers around the world. We once had something unique and wonderful, and it is gone.

Much of this memoir was written while I was at the Aspen Center for Physics. For many years Coleman would spend every other summer at the center. He was very proud of having learned to ride a bicycle there 20 years ago. His wife Diana taught him to ride on the tennis courts near the center, and cycling became an important part of his life. He cared deeply about the Aspen Center for Physics and at various times was an advisory board member and trustee. It was inspiring to remember Coleman's contributions in a place that along with Erice, in Italy, he loved as much as any place in the world. I hope that this memoir will serve as a lasting reminder of the contributions of the Aspen Center for Physics to the community.[7]

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NOTES

1. Though they were certainly understood and used by some mathematically sophisticated theorists; see, for example, R. Utiyama's paper (1956) generalizing Yang-Mills theory (Yang and Mills, 1954) to an arbitrary Lie group.

2. As reported in the delightful memorial by Roberta Gordon in the *Harvard Gazette*, Nov. 29, 2007, *news.harvard.edu/gazette/story/2007/11/sidney-coleman-dies-at-70/*. For additional Coleman stories see the blog at *betsydevine.com/blog/2007/11/20/our-friend-sidney-coleman-has-left-the-planet/*.

3. The full story is told in Politzer's Nobel Prize lecture in which Politzer (2005) refers to Coleman, for good reason, as "my beloved teacher."

4. *physics.harvard.edu/about/video.html*.

5. *efanzines.com/EK/eI10/index.htm*.

6. *efanzines.com/EK/eI36/index.htm#sid*.

7. This material is based upon work supported by the National Science Foundation under grants no. 0804450 and 1066293. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Science Foundation.

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