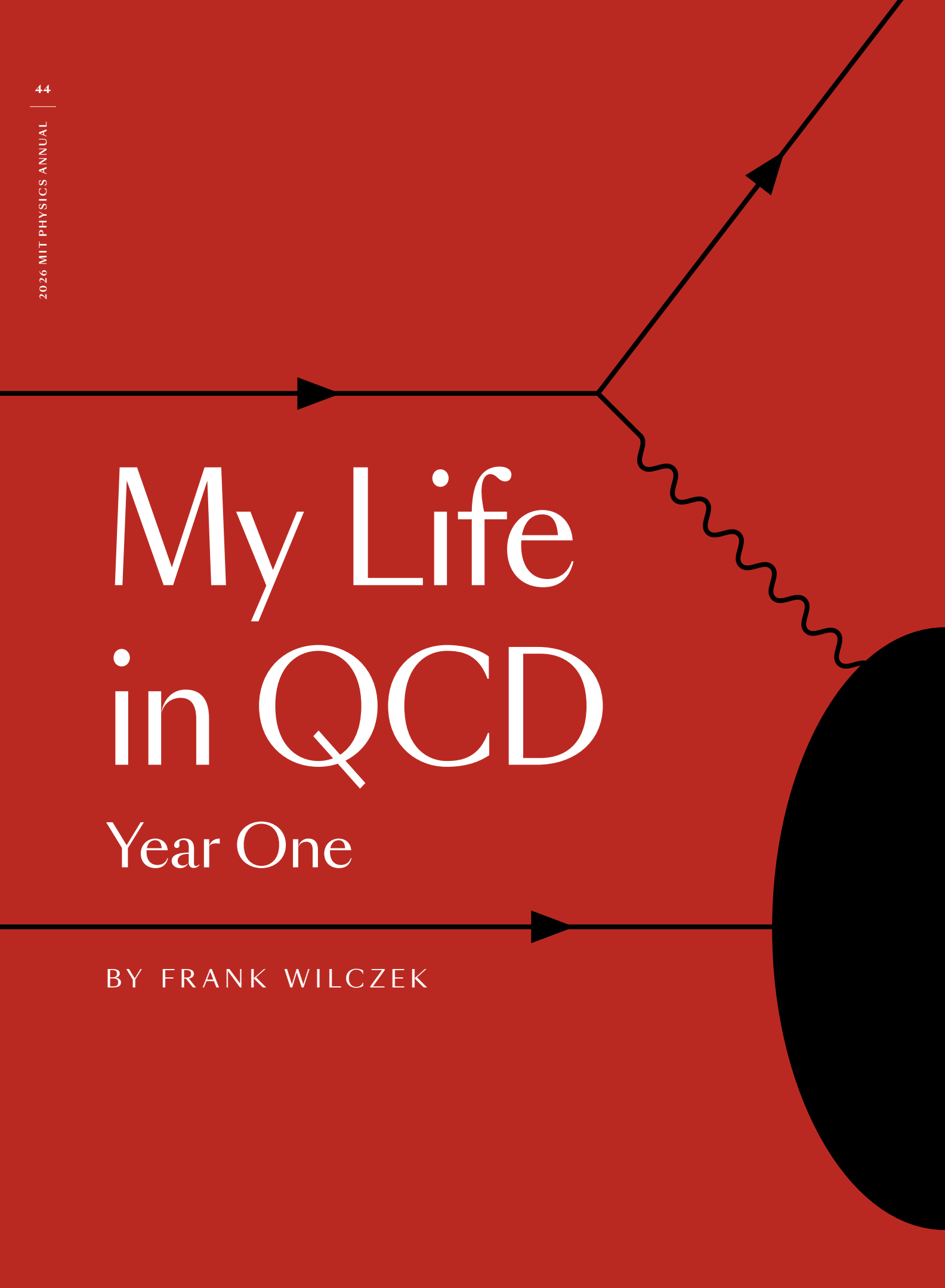


A Feynman diagram is drawn in black lines on a red background. It features two horizontal lines with arrows pointing to the right. The top line has a vertex where a wavy line (representing a gluon) branches off to the right and upwards. The bottom line has a vertex where a solid line branches off to the right and upwards, meeting the wavy line. A large black semi-circle is positioned on the right side of the diagram, partially overlapping the wavy line and the bottom horizontal line.

My Life in QCD

Year One

BY FRANK WILCZEK

In the winter of 1972 I was a struggling, lonely graduate student at Princeton, in the process of converting from pure mathematics to physics. I had spent two years “in the wilderness” after graduating from the University of Chicago, during which I lacked clear direction.

That summer and fall, two miracles occurred. In the summer I met Betsy Devine. Wandering in the wilderness ceased to be an acceptable option. (A year later, on July 3, 1973, Betsy and I got married. We recently celebrated our golden anniversary.)

The second miracle was the beginning of an intense collaboration with David Gross, my new thesis advisor. This work soon bore spectacular fruit. It was beginning of modern QCD, and of my love affair with it. Thereby hangs a tale ...



Asymptotic freedom as a theoretical discovery

David and I considered many possible projects to pursue. We converged on a problem area that was both fundamentally interesting and relevant to his program of showing that quantum field theory could not describe the strong interaction. (More on that shortly, below.)

There were two big recent developments in theoretical physics that were not yet widely known, nor fully digested, in the research community. They offered

FIGURE 1:

(a) A test charge inserted into a dielectric medium polarizes the surrounding molecules. As a result its influence is diminished (screened) far away. An analogous screening effect, known as vacuum polarization, arises from the polarization of virtual particle-antiparticle pairs (and other quantum fluctuations). (b) Vacuum polarization can be calculated using Feynman graphs. It becomes singular at short distances, leading to catastrophic screening.

new approaches to fundamental problems—and, crucially for me, lots of potential thesis fodder. These were the renormalization group, on the one hand, and non-abelian gauge theories on the other.

The renormalization group is a collection of methods for investigating what a mathematical model predicts for physical behavior in

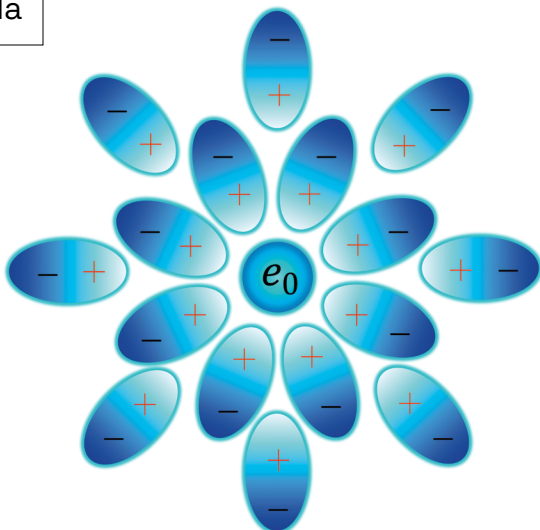
extreme circumstances. Ken Wilson had recently injected powerful new ideas into the subject, for which he eventually (in 1982) was awarded the Nobel Prize. He gave a brilliant series of lectures about his new ideas at Princeton, that both David and I attended.

Non-abelian gauge theories are a specific way of constructing equations that are consistent with the basic principles of special relativity and quantum mechanics. Those principles are quite constraining, so such constructions are few and far between. Non-abelian gauge theories are mathematically elegant—the equations display a tremendous amount of symmetry—but they are challenging to work with. Adequate tools for the job became available around 1970, mainly through remarkable work by Gerard 't Hooft and Martinus Veltman, for which they eventually (in 1999) were awarded the Nobel Prize.

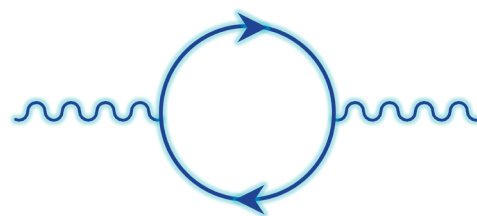
It was, then, a natural and attractive problem to investigate whether and how one could bring those two developments, the renormalization group and non-abelian gauge theory, together. It offered fresh perspectives on a profound issue that, for arcane reasons, is known as “the Landau ghost.” Here I’ll describe the problem in a way that doesn’t bring in spooks.

Figure 1a shows how screening works in a dielectric material. A positive test charge, by attracting negative and repelling positive charges, distorts the surrounding molecules in such a way that it is, in effect, surrounded by a cloud of negativity that reduces the field it would otherwise generate. We say that the test charge is (partially) screened. A version of this effect also occurs in empty space. In that case you have to imagine the picture to be a snapshot in time, and the molecules to be quantum fluctuations or, in more vivid language, virtual particle-antiparticle pairs. Each fluctuation—

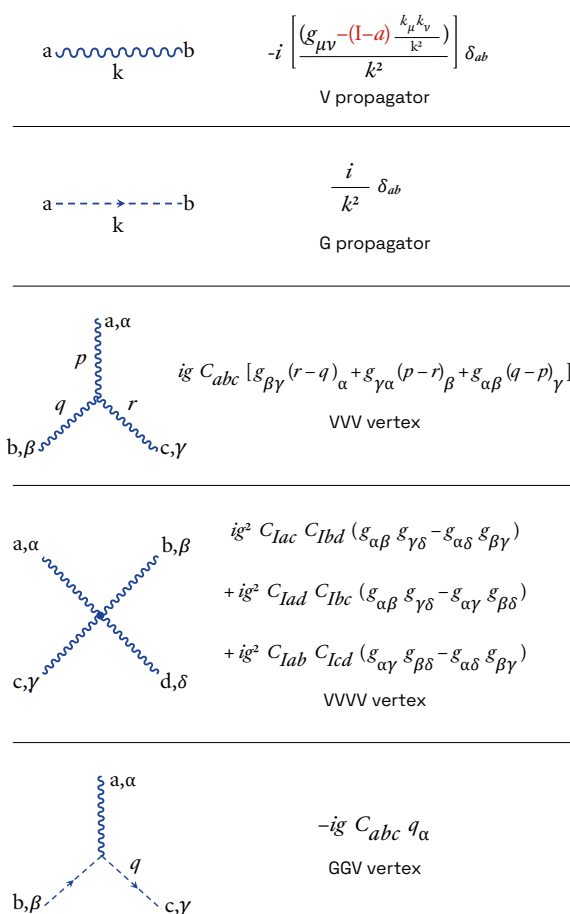
1a



1b



$$e_0 < \infty \Rightarrow e_\infty = 0$$



or, alternatively, each virtual pair—is short-lived, but new ones constantly arise to replace them. These vivid, dynamic effects in space-time are difficult to visualize

FIGURE 2:
The Feynman rules for a pure Yang-Mills theory (all momenta flow into the vertices). Non-abelian gauge theories introduce new kinds of quantum fluctuations, and it gets complicated to calculate vacuum polarization. This partial inventory of its building-blocks gives some impression of that complexity.

so large that any test charge we insert gets *completely* screened. Any finite “bare” test charge e_0 results in vanishing observable charge e_∞ .

Landau and his school investigated this phenomenon in a wide variety of quantum field theories, as did Zee and, most systematically, Coleman and Gross. All known theories exhibited the same sort of catastrophic screening. It disturbed Landau so badly that he wrote:

We are driven to the conclusion that the Hamiltonian method for the strong interaction is dead and must be buried, although of course with deserved honor.

I had encountered that quote in my reading, and it made a big impression on me.

None of those existing calculations of screening used the new non-abelian gauge theories. Taking them on posed both practical and conceptual challenges. If those challenges could be overcome, the renormalization group would tell us whether or not the new theories, like the old, had catastrophic screening—in other words, whether they were haunted by the Landau ghost. If so, the popular electroweak theories had a serious problem. If not, we could calculate how they behaved at short distances. Either answer would be interesting, and help me to get my degree.

The main practical challenge was, simply, algebraic complexity. You can get a glimpse of that challenge from a glance at Figure 2. There you see displayed the basic building-blocks of the minimal non-abelian gauge theory. These building-blocks had to be combined into more complex expressions, which then go into integrals, according to the rules for Feynman graphs. The resulting integrals are, on the face of it, both infinite and gauge dependent. (In order to do practical calculations in gauge theories one must do something analogous to choosing a coordinate system, which here we call choosing a gauge. But physically meaningful results cannot depend on how you choose the gauge, just as geometrically meaningful results cannot depend on your choice of coordinate system.)

We had hand-waving arguments that the renormalization group was consistent with gauge independence, but no reliable proof. This was a big conceptual challenge. Sidney Coleman, a masterful Harvard physicist and fast friend who was on leave at Princeton, took great interest in what we were doing. He emphasized it to me. I felt compelled to answer his questions experimentally, so to speak, by doing the calculations using several different kinds of test charges using several different ways of choosing a gauge. In other words, I took on many different complicated calculations that I hoped—and expected—would all give the same final answer. That, to me, would be more convincing than any abstract formal proof. (The abstract proof could, and did, come later.) To be safe, I also tested my processing procedures—

which were unconventional but streamlined the calculations—in all the older theories, where we already knew the right answer.

The calculations were “straightforward in principle.” But over time, as we followed through on them, that phrase (which we often used) became something of a joke between David and me. After several weeks of labor, anxiety, and de-bugging, all my calculations finally did converge on the same answer, as we had hoped. And that answer, as summarized in Figure 3, was a thing of beauty. The new theories escaped the screening catastrophe. Instead, they had the opposite property: anti-screening. With anti-screening, a finite observable charge at large distance corresponds to an infinitesimal bare charge at small distances.

$$\beta(g) = -\frac{g^3}{16\pi^2} \left(\frac{11}{3} N_c - \frac{4}{3} \frac{N_f}{2} \right)$$



Anti-screening is a much healthier situation than screening, theoretically, since we build up the theory starting from the primary interactions that occur at short distances, and therefore involve bare charges.

Following Sidney’s suggestion, we called the phenomenon that the basic interactions in non-abelian gauge theories become feeble at short distances, and ultimately turn off, “asymptotic freedom.”

Asymptotic freedom as an experimental reality

The Geiger-Marsden experiment of 1912, pictured in Figure 4a, was a milestone event for modern physics. When alpha particles from a radioactive source impinged on a gold foil, they were sometimes deflected through large angles. Ernest Rutherford, who had suggested the experiment, quickly supplied a convincing interpretation of its result. From the observed distribution of deflection angles you can infer the forces that caused them, as indicated in Figure 4b. Rutherford deduced, from the observed pattern of deflections, that most of the mass of gold atoms was concentrated in a small heavy nucleus, that contained most of the atom’s mass and all of its positive

electric charge. The required force could then be ascribed to ordinary electrical repulsion between the alpha particles and the gold nuclei.

The model of atoms that emerged from this experiment, featuring a small, positively charged nucleus surrounded by a cloud of (negatively charged) electrons, was taken up by Bohr, who introduced rules suggested by the nascent ideas of quantum theory. For several years, the application of quantum ideas involved a lot of guesswork. A mature version of quantum theory, based in unambiguous equations and algorithms, emerged in 1924–1925, primarily through the work of Heisenberg and Schrödinger. Though many refinements came in later, their ideas laid the foundation for the theory of atoms we still use today.

FIGURE 3: The central result of the calculation is the formula displayed here, taken from the poster for the 2004 Nobel Prize. It gave anti-screening, as opposed to screening, and thereby eliminated the “Landau ghost.” The photos are contemporary pictures of (from left) David Gross and me.

The frontier of exploration in fundamental physics moved inward, to the atomic nuclei. Their very existence was evidence for a new force, beyond the previously known forces of electromagnetism and gravity. The electrical repulsion among like

charges wanted to blow them apart, and gravity was much too feeble to hold them together. The new force would have to be very powerful, so it got called the strong force. Apart from its name, however, almost everything about this force remained mysterious for many years. Study of the strong force led to discovery of many interesting phenomena and insights, notably including the transmutation of elements, the source of stellar energy, nuclear weapons, and the existence of many new particles. But a fundamental theory remained elusive. In 1970, at the dedication of Fine Hall in Princeton, Freeman Dyson opined that no such theory would emerge for a hundred years.

In hindsight, we can see that the crucial experiment was a beautifully logical follow-up to the work of Geiger, Marsden, and Rutherford. It was done by a team led by Jerome Friedman, Henry Kendall, and Richard Taylor starting in the late 1960s, and led to a Nobel Prize in 1990. The new work featured two innovations. The first was simply to work at much higher energies, using ideally simple particles as projectiles—electrons, in the original experiments. Geiger-Marsden was a table-top experiment, but Friedman-Kendall-Taylor was a job

for the Stanford Linear Accelerator (SLAC), shown in Figure 4c, which is two miles long. High energy is necessary due to the wave nature of electrons, which

FIGURE 4:

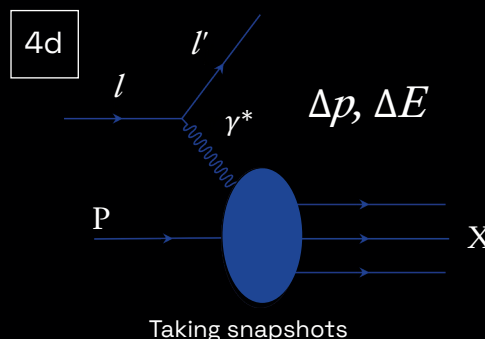
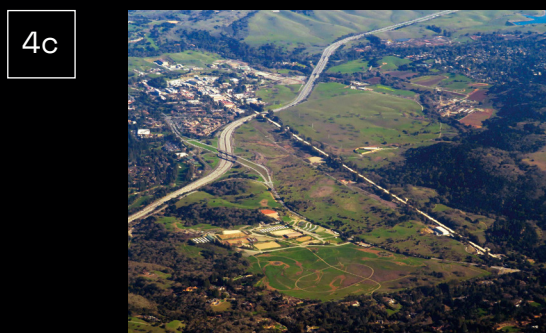
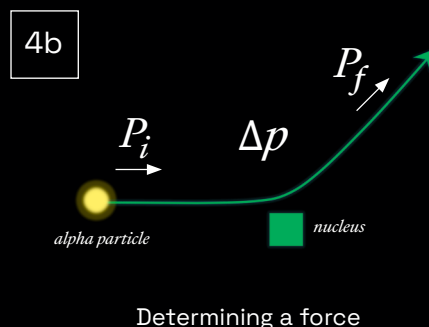
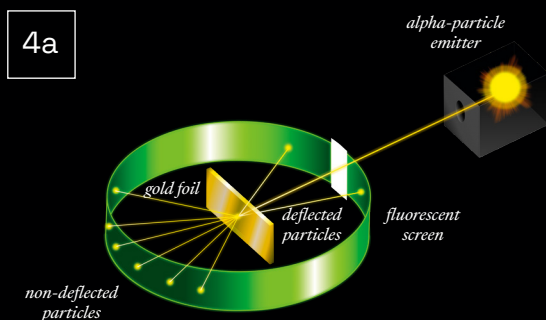
(a) The original Geiger-Marsden experiment, a table-top experiment that revealed the existence of atomic nuclei but did not resolve their structure. (b) The principle behind the experiment: by measure the deflections of projectiles, one can infer the forces that caused them. (c) The Stanford Linear Accelerator (SLAC), a two-mile long device that produced beams of high-energy electrons. Credit: Pi.1415926535, CC BY-SA 3.0 <<https://creativecommons.org/licenses/by-sa/3.0/>>, via Wikimedia Commons. (d) By keeping track of both deflection and energy losses of the projectile electrons, one resolves their causes in both space and time.

cross-sections to snapshots of proton interiors is a sophisticated exercise in image processing, but straightforward in principle.

implies that good resolution in space requires large changes in momentum. The second was to study not only the angles of deflection, but also the pattern of energy losses—what physicists call inelastic scattering. Whereas changes in angle correspond to changes in momentum, which empowers good spatial resolution, changes in energy empower good resolution in time, as indicated in Figure 4d. This turns out to be crucial, because things move very fast inside protons. The translation from scattering

Strikingly clear pictures of proton interiors emerged from this work. They revealed that protons are built up out of simpler particles. The existence of some of those particles—quarks—was not entirely surprising, since phenomenological models using quarks had been helpful in other connections. But there had to be some additional electrically neutral “dark matter” inside protons, since the observed quarks gave only about half of the total energy stored in protons (according to $m = E/c^2$), but all of their charge. The most surprising and paradoxical aspect of the pictures, however, was precisely their clarity. Since quarks participate in the strong interaction, we might anticipate that they would exchange energy and momentum with each other, and, presumably, with the subnuclear “dark matter.” Such exchanges would distort the changes in energy and momentum of the electron of the scattered electron in Figure 4d. In effect, the electron wouldn’t be viewing the quark itself but only its image as processed through a medium.

That heuristic argument could be made mathematically precise, as shown by Callan and Gross. If the strong interaction was always strong, you could not understand the Friedman-Kendall-Taylor pictures. David suspected that any quantum field theory would make strong interactions observed at nuclear distances even stronger forces at subnuclear distances: the screening effect we



discussed earlier. Had that been the case it would have vindicated Landau's call for a burial, and a fresh start.

But asymptotic freedom revealed a profoundly simple, radically conservative alternative. If the strong interaction was governed by an asymptotically free theory, it would not always be strong. In fact good resolution in space and time would begin to reveal the bare charges, which interact feebly and therefore *can* be imaged sharply. We could hope to understand the pictures in quantum field theory, after all—but only if we assume that the theory of the strong interaction is asymptotically free.

The theory of the strong interaction

Asymptotic freedom pointed us toward a specific *kind* of theory for the strong interaction, but it wasn't

FIGURE 5:

(a) Mickey Rooney's Downingtown Inn, the site of my first physics conference.
(b) This sign "No boring people allowed" inspired a performance by Feynman. He made a show of studying it, strode through, and gave a challenging stare to his entourage, before waving them in, deadpan.

immediately clear to us that it pointed to a specific theory. It had to be a non-abelian gauge theory, and (based on the SLAC pictures) it had to contain quarks. Those ingredients were necessary, but were they sufficient? David and I explored many alternatives, but all of them were ugly, physically flawed, or both. They generally predicted new features in the pictures, and new particles, for

which there was no evidence. We soon convinced ourselves that the minimal theory was likely to be the right one. It is the theory we now call quantum chromodynamics (QCD)—and it proved to be the right one.

Our failed attempts to find viable alternatives to QCD for the theory of the strong interactions were not entirely fruitless, though. Through those explorations, we expanded the repertoire of quantum field theory. The more general models can be, and have been, repurposed. They supply adventurous models that promise to augment and unify our account of fundamental interactions, and to give new perspectives on the early universe.

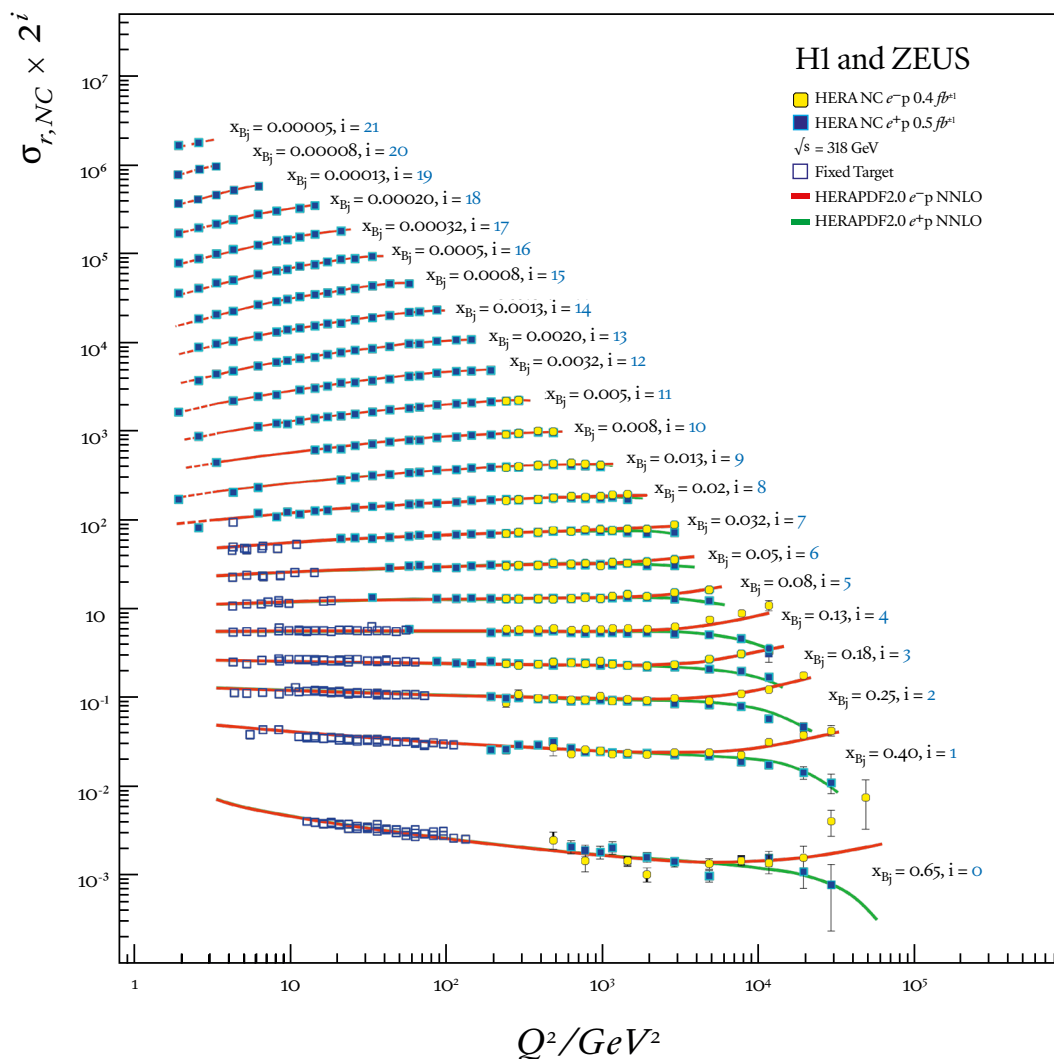
The emergence of QCD as a uniquely attractive realization of asymptotic freedom transformed the problem of the strong interaction. In place of the broad research programs and fragmentary insights that had characterized earlier work, we now had a single, specific candidate theory—a theory that could be tested, and perhaps falsified, but which could not be fudged. Even now, when I re-read our declaration:

Finally let us recall that the proposed theories appear to be uniquely singled out by nature, if one takes both the SLAC results and the renormalization-group approach to quantum field theory at face value.



5a

5b



I relive the mixture of exhilaration and anxiety that I felt at the time.

Having settled on specific, well-motivated candidate equations for a complete, definitive theory of the strong interaction, we were faced with the challenge of drawing out testable, quantitative consequences. We hoped, of course, that our theory would be right, but also—and to me, at least equally important—that it would be fruitful.

In the early days, our ability to draw out testable predictions was very limited. We could calculate how the strong interaction worked at short distances and very high energies, but most experiments in particle physics bring in a complicated mixture of distances and energies. The outstanding exception was deep inelastic scattering à la Friedman-Kendall-Taylor where you could focus on short distances and, with more powerful accelerators, higher energies. We worked hard, using asymptotic freedom and the renormalization group, to

calculate what the theory predicted for those kinds of experiments.

FIGURE 6:

The quantitative comparison of theory and experiment for our non-abelian gauge theory of the strong interaction was very crude at first, but after a few years it came to look like this. Credit: Abramowicz, H., Abt, I., Adamczyk, L. *et al.* Combination of measurements of inclusive deep inelastic scattering cross sections and QCD analysis of HERA data. *Eur. Phys. J. C* 75, 580 (2015). <https://doi.org/10.1140/epjc/s10052-015-3710-4>.

The results brought both good news and bad news. The good news, was that we got very specific predictions. Testing them was “straightforward in principle.” The bad news, was that it appeared that in practice they would be extremely difficult to test. We predicted that certain quantities—technically, moments of structure functions—would vary as powers of logarithms as you change the energy. The problem is that it takes big changes in energy to make small changes in its logarithm. Sam Treiman, a wise and experienced friend and professor at Princeton, told me “People never

measure logarithms.” Though he said it with a smile, that sobering thought brought me down to earth.

A few weeks later, though, I got a big boost. It was at my first-ever conference, a small workshop on high energy physics at the Downingtown Inn, in the Philadelphia suburbs (Figure 5). Feynman was there, and he gave the closing summary talk. But instead of simply summarizing the workshop—which was all over the map—he devoted half his talk to describing our predictions and urging the experimentalists to take them seriously! He said our theory was probably wrong, but maybe not, and it deserved to be tested, even though that would be tough. Feynman had long been a big hero for me, and for him to focus on my work was, to me, an almost incredible affirmation.

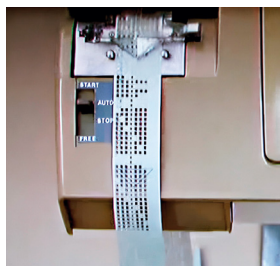


FIGURE 7: Using computers was a very different experience in the early 1970s. My early versions of the theory calculations that go into Figure 6 were done in late night and early morning sessions on Val Fitch’s PDP-11.

than we drew initially, and experimentalists learned new ways of organizing their data. A key idea, generalizing the lesson of SLAC, was to focus on flows of energy and momentum (“jets”), rather than individual particles.

During QCD’s childhood, success was uncertain but progress was rapid. The sessions of high energy physics conferences devoted to “Testing QCD” were, consistently, exciting and well-attended highlights.

And the experimental community did rise to the challenge, way beyond anything I anticipated. Within a few years, we had results like what’s shown in Figure 6. The measured results agreed beautifully with the output I coaxed out of Val Fitch’s PDP-11 (Figure 7) in early morning sessions on borrowed time. It turned out that sufficiently determined people could measure logarithms, after all.

Over the remainder of the twentieth century, and continuing to this day, theorists learned how to calculate many more consequences of QCD



FIGURE 8: A wise fortune cookie.

Eventually, though, people got tired of testing the theory. The novelty of success had worn off; it had become a routine expectation. Nowadays the same kind of work that used to be called “Testing QCD,” but now carried out with much greater sophistication and accuracy, is called “calculating backgrounds.” That can be an important activity, enabling new discoveries. Notably, the discovery of the Higgs boson was powered by QCD. Still, maturity is a bittersweet experience.

Hopeful calculation

Looking back, it seems remarkable to me how much we learned by following the strategy of *hopeful calculation*. Plowing ahead, we postponed many hard technical issues involving infrared divergences, confinement, gauge invariance, and experimental feasibility. We calculated what we could and learned by doing. My all-time favorite Chinese fortune cookie (Figure 8) contained this gem:

The work will teach you how to do it.

That gets it right.

FRAMING

This piece is based on the first quarter of my David M. Lee lecture “My Life in QCD: A Fifty-Year Love Affair, Still Going Strong,” at Harvard University, April 9, 2024. Related material appeared in my Nobel lecture: <https://www.nobelprize.org/prizes/physics/2004/wilczek/lecture/>, in my keynote “QCD at 50: Golden Anniversary, Golden Insights, Golden Opportunities,” at the 2023 Erice summer school, <https://arxiv.org/pdf/2403.06038>, and “Triumph, Window, Clue, and Inspiration: The Higgs Particle in Context,” by Frank Wilczek. physics@mit 2013; 36–45. These contain extensive references. All figures provided by Frank Wilczek and Juliana Baena Rodríguez.

PROFESSOR FRANK WILCZEK is considered one of the world's most eminent theoretical physicists. When only 21 years old and a graduate student at Princeton University, in work with David Gross he defined the properties of color gluons, which hold atomic nuclei together. This earliest research included the discovery of asymptotic freedom and the formulation of quantum chromodynamics, as discussed in this article. Later highlights include the invention of axions and discovery of their potential role in cosmology, and the discovery and exploitation of new forms of quantum statistics (anyons), the discovery and investigation of color-flavor locking, and the proposal of time crystals. "Axions," "anyons," "color-flavor locking," and "time crystals" are all terms that he introduced. They have come to define major topics in physics research.

Frank Wilczek received his BS degree from the University of Chicago and his PhD from Princeton University in 1974. He remained at Princeton through 1980, rising to Professor. During 1981–1988, he was the Chancellor Robert Huttenback Professor of Physics at the University of California at Santa Barbara, and the first permanent member of the National Science Foundation's Institute for Theoretical Physics. In the fall of 2000, he moved from the Institute for Advanced Study (1989–2000), where he was the J.R. Oppenheimer Professor, to the MIT Department of Physics, where he is now the Herman Feshbach Professor of Physics, Post-Tenure, and where he used to have an office. He is now tenured as the Wager Professor of Physics at Arizona State University (ASU). He has also been Professor at Stockholm University and NORDITA since 2016. In recent years Wilczek has also been active in China. During 2017–2022, he served as Founding Director of the T. D. Lee Institute in Shanghai. Since 2016, he is Chief Scientist at the Wilczek Quantum Center, sponsored by Shanghai Jiao-Tung University (STU) and University of Science and Technology in China (USTC).

Wilczek has been a Sloan Foundation Fellow (1975–1977) and a MacArthur Foundation Fellow (1982–1987). He has received UNESCO's Dirac Medal (UNESCO), the Lorentz Medal (Netherlands Academy of Sciences), the American Physical Society's Sakurai and Lilienfeld Prizes, and several others. In 2004 he received the Nobel Prize in Physics, and in 2005 the King Faisal Prize. In 2022, he was honored with the Templeton Prize. In 2022, Wilczek gave the initial Steven Weinberg Memorial lecture at the University of Texas, Austin. He is a member of the American Academy of Arts and Sciences, and the U.S., the Netherlands, the Swedish, and the Chinese Academies of Sciences, among others.

In 2015, he co-founded the Quantum Connections international summer school near Stockholm, and in 2025, its sister winter Quantum Connections in Sanya, China. Since 2018, the Jagellonian University (Krakow) has awarded a biannual "Wilczek Prize" for young Polish physics researchers. These institutions continue to thrive.

During 2015–2023, Wilczek wrote a monthly "Wilczek's Universe" column for the *Wall Street Journal*; this evolved into an ongoing "Wilczek's Multiverse" series at the *South China Morning Post*. He has authored several well-received books for the public that are published by leading commercial publishers and widely translated, notably including "Longing for the Harmonies" (with Betsy Devine) (WW Norton & Co, 1988), "A Beautiful Question" (Penguin, 2015), and "Fundamentals" (Penguin, 2021). Presently he is working on "Futures" (Penguin, expected 2027), an examination of how science, by defining possible futures, can inform the search for purpose. He is also editor-in-chief of "The Princeton Companion to Physics" (Princeton University Press, expected 2029).