The Yang-Mills Model

by Sheldon Lee Glashow

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Gauge theories are relevant to contemporary physics because the standard theory of particle physics is based on a generalization of the Yang-Mills model, the first non-abelian gauge theory dealing with particle symmetries. Furthermore, gauge interactions have a natural origin in the context of superstring theory.[2] The symmetries of physics may be exact, approximate, or alleged. Some symmetries are discrete; others, continuous. Among the discrete symmetries of particle physics are three long thought to be exact: space-reflection or mirror symmetry P, time-reversal symmetry T, and charge conjugation C, which interchanges particles and antiparticles. All three were known to be exact symmetries of strong and electromagnetic interactions.

In the mid-twentieth century, experimental physicists astounded themselves and their theoretical colleagues by discovering that none of these operations, nor a product of any two of them, is respected by the weak interactions. Only their product, CPT, remains as an exact symmetry of nature.

In 1918, the German mathematician Emmy Noether proved that every continuous symmetry of a physical system entails a conservation law.[3] For example, the laws of energy and momentum conservation follow from the fact that experiments yield the same results wherever and whenever they are done. There are, all told, ten different continuous space-time symmetries: time translation, three directions along which to translate, three axes about which to rotate, and three directions along which to move. These invariances correspond respectively to conservation laws for the energy, momentum, angular motion, and constant center-of-mass velocity of an isolated system.

Other continuous symmetries are internal. They refer to intrinsic properties of particles rather than space and time. Thus invariance under appropriately chosen phase changes of complex quantum fields yields conservation laws for electric charge, baryon number, and lepton number.[4] Charge conservation is well established as an exact conservation law, but theorists have excellent reasons to believe that neither baryon number nor lepton number is exactly conserved. Experimental physicists have struggled for decades to detect instances of nucleon decay or lepton-number violation. They have had no success, but they still try, in deeper mines and with ever larger and more sensitive equipment.

James Clerk Maxwell's 1865 "A Dynamical Theory of the Electromagnetic Field" was the first theory to display gauge invariance. Today his theory is most conveniently formulated in terms of the four-component vector potential, A_μ, whose derivatives

[1] Sheldon Lee Glashow, "The Yang-Mills Model", Inference: International Review of Science 5, no. 2 (2020), doi:10.37282/991819.20.1, https://inference-review.com/article/the-yang-mills-model.

[2] For a more thorough discussion of the history and phenomenology of gauge theories, see Álvaro de Rújula, "Fifty Years of Yang-Mills Theories" (2004), arXiv:hep-ph/0404215v4.

[3] Emmy Noether, "*Invariante Variationsprobleme*," *Nachrichten von der Gesellschaft der Wissenschaften zu Gottingen, Mathematisch-Physikalische Klasse* (1918): 235–257. See also Nina Byers, "E. Noether's Discovery of the Deep Connection between Symmetries and Conservation Laws," *Israel Mathematical Conference Proceedings* 12 (1999): 67–82.

[4] Any particle made up of three quarks (like the neutron or proton) is a baryon; leptons are particles like electrons and neutrinos that have no strong interactions. There are known to exist six different flavors of quark and six different species of lepton. Both quarks and leptons are spin-1/2 fermions.

yield electric and magnetic fields. However, A_μ itself is neither directly observable nor well defined. In the context of quantum field theory, its ambiguity reflects the invariance of electric and magnetic fields under a gauge transformation

$$A_\mu \to A_\mu + \partial_\mu \varphi, \text{ and } \psi \to e^{iq\varphi}\psi,$$

for every electrically charged field ψ, where q is its charge and φ is an arbitrary function of space and time. Electromagnetism is an abelian gauge theory because gauge transformations commute. It is also a local symmetry, in the sense that gauge transformations depend explicitly on space and time. In the context of quantum electrodynamics, gauge invariance requires the existence of massless photons coupled to all electrically charged particles.

Albert Einstein's 1915 general theory of relativity can be regarded as a gauge theory,[5] although the precise nature of its gauge invariance may be somewhat controversial. His earlier special theory of relativity pronounced the independence of physical laws, especially those of electromagnetism, from the choice of inertial coordinate system. It embodies invariance under transformations of the Lorentz group and establishes the universality of the speed of light. With the risk of oversimplification, we may say that general relativity permits the choice of coordinate frame to depend on space and time, thereby making Lorentz invariance a local symmetry and yielding a non-abelian gauge theory of gravity. Quantum theory suggests that the self-interacting particle avatars of gravitational waves are massless spin-2 gravitons, particles unlikely to be directly observed due to the weakness of gravitational forces.

In 1932, Werner Heisenberg introduced the first non-abelian internal symmetry group. By an internal symmetry he meant one related to a particle's identity, and not to displacements or rotations of space-time. Taking account of the near equality of neutron and proton masses—to within about a tenth of a percent—he proposed that nuclear forces cannot distinguish between these two so-called nucleons. Specifically, he assumed the strong interactions to be invariant under all unitary unimodular transformations among them. Heisenberg's notion, based on the Lie group SU(2), became known as isotopic spin symmetry, in analogy with the earlier notion of spin as angular momentum. Spin has to do with rotations in real space, while isotopic spin, or isospin, has to do with an imagined but fictive three-dimensional space.

[5] E.g., Ryoyu Utiyama, "Invariant Theoretical Interpretation of Interaction," *Physical Review* 101, no. 5 (1956): 1597–1607, doi:10.1103/physrev.101.1597; Tom Kibble, "Lorentz Invariance and the Gravitational Field," *Journal of Mathematical Physics* 2, no. 212 (1960), doi:10.1063/1.1703702.

All strongly interacting particles, generically termed *hadrons*, should and do appear as isospin multiplets, such as the triplet of pions, doublet of kaons, and a quadruplet of pion-nucleon resonances. Although isospin symmetry proved to be very useful in both nuclear and particle physics, it cannot be an exact symmetry of nature. Protons are electrically charged, neutrons are not. What is more, neutrons become protons in the course of radioactive beta decay. Isospin symmetry of nuclear forces is not shared with electromagnetism nor with the weak interactions.

In 1954, Chen Ning Yang and Robert Mills suggested that Heisenberg's isospin symmetry based on SU(2) be extended, so as to become a local gauge symmetry. "[W]e wish to explore the possibility," they wrote, "of requiring all interactions to be invariant under *independent* [emphasis original] rotations of the isotopic spin at all space-time points."[6] They proposed the first non-abelian gauge theory of internal symmetries. Just as electromagnetic gauge invariance requires the existence of massless photons, so Yang-Mills symmetry invokes three massless vector gauge bosons, two with opposite electric charges, one neutral. The authors were aware that no such particles exist: their proposed symmetry cannot be exact. They continued:

> [T]o the question of the mass [of the gauge fields]… we do not have a satisfactory answer … A conclusion about [their] mass is of course very important in deciding whether the proposal… is consistent with experiment.[7]

Amen!

In 1957, my thesis advisor Julian Schwinger published "A Theory of the Fundamental Interactions," a paper summarizing what he had previously presented at his Harvard courses.[8] It began with an epigraph by Einstein: "The axiomatic basis of theoretical physics cannot be extracted from experience but must be freely invented" Thereupon Schwinger introduced the notion of a unified theory of weak and electromagnetic interactions:

> Is there … a family of *bosons* [emphasis original] that realizes the $T = 1$ representation of the three-dimensional rotation group? The exceptional position of the electromagnetic field in our scheme, and the formal suggestion that this field is the third

[6] Chen Ning Yang and Robert Mills, "Conservation of Isotopic Spin and Isotopic Gauge Invariance," *Physical Review* 96, no. 191 (1954): 192, doi:10.1103/PhysRev.96.191. Mills once remarked, "I am only a name attached to a brilliant idea of Yang's" (Álvaro de Rújula, private communication). The concept was independently developed by Ronald Shaw, then a graduate student (unpublished, and Cambridge University PhD thesis, September 1955).

[7] Yang and Mills, "Conservation of Isotopic Spin," 195.

[8] Julian Schwinger, "A Theory of the Fundamental Interactions," *Annals of Physics* 2, no. 407 (1957), doi:10.1016/0003-4916(57)90015-5.

> component of a three-dimensional isotopic vector, encourage an affirmative answer. We are thus led to the concept of a spin-one family of bosons, comprising the massless, neutral, photon and a pair of electrically charged particles [$Z^{\pm}$] that presumably carry mass … From its role as the partner of the electromagnetic field, we might expect that the charged *Z* field interacts universally with electric charge, or rather, changes of charge, without particular regard to other internal attributes…[W]e have been led to a dynamics of a charged, unit spin *Z*-particle field that is interpreted as the invisible instrument of the whole class of weak interactions.[9]

Oddly, Schwinger never mentions gauge theories in his paper, nor does he cite the work of Yang and Mills, although he was surely aware of it.

Schwinger is likely to have been the first scientist to put forward the possibility of a unified theory of weak and electromagnetic interactions.[10] For my thesis, he said I should try to create such a theory, one that could account for recent developments in particle physics. Following his lead, I imagined the existence of a heavy charged intermediary of weak interactions. The problem, as I saw it, was to create a mathematically acceptable version of the model which could incorporate the then-recent observations of parity violation and the newly proposed V-A theory of weak interactions. I found two reasons that required Schwinger's model to be a gauge theory: the magnetic moment of Schwinger's $Z^{\pm}$ had to be that of a Yang-Mills gauge theory. Otherwise, the massless and symmetric version of the theory would not exist,[11] and the one loop weak radiative correction to the magnetic moment of the electron would diverge.[12] With that doubly magic value of the charged boson's magnetic moment, Schwinger's proposal becomes that of a badly broken gauge theory. I found no way to incorporate parity violation into my advisor's Yang-Mills model. Nonetheless I concluded prophetically:

> It is of little value to have a potentially renormalizable theory of [weak interactions] without the possibility of a renormalizable electrodynamics. We should care to suggest that a fully acceptable theory of these interactions may only be achieved if they are treated together.[13]

I passed my oral exam, received my doctorate, and set off for Copenhagen.

In 1960, as I was completing my National Science Foundation postdoctoral fellowship at Niels Bohr's *Institutfor Teoretisk Fysik*, I realized that Schwinger's Yang-Mills model could not work. A larger gauge group was needed to account for parity violation. I found that that could be done with the simplest possible extension of the gauge group: a gauge theory based on SU(2) × U(1), the Lie group underlying today's electroweak theory.[14] The photon was identified as a linear combination of the two neutral gauge fields. The orthogonal linear combination corresponds to the neutral weak intermediary Z^0, which would mediate novel neutral current interactions. The charged gauge bosons are now called $W^{\pm}$. I had no idea how these particles could acquire mass without threatening the potential renormalizability of the theory. Any attempt to include hadrons in the theory seemed to require the existence of experimentally excluded strangeness changing neutral current phenomena. These problems would be solved within the next decade.

In that same year, my good friend from Harvard, Jun John Sakurai, applied the Yang-Mills model to the *strong* nuclear force. "Following Yang and Mills," he wrote,

> we require that the gauge transformations that are associated with the three "internal" conservation laws—baryon conservation, hypercharge conservation, and isospin conservation—be "consistent with the local field concept that underlies the usual physical theories."[15]

Here Sakurai is quoting Yang and Mills. "It is suggested," Sakurai goes on to write, "that every conceivable experimental attempt be made to detect directly… the vector fields introduced in the theory." He proposed a gauge theory based on the group SU(2) × U(1) × U(1), which includes five strongly interacting massless gauge bosons, two charged and three neutral. Additional unspecified interactions would be needed to break the gauge theory and provide masses

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9 Schwinger, "Theory of the Fundamental Interactions," 424–425, 433.

10 Long before, Hideki Yukawa hoped that his then-hypothetical "mesotrons" could mediate both strong and weak forces. Hideki Yukawa, "On the Interaction of Elementary Particles," *Proceedings of the Physico-Mathematical Society of Japan* 17 (1935): 48–57. His particles (now called pions) exist, but they do not mediate weak interactions. Others, including Albert Einstein, Erwin Schrödinger, and Hermann Weyl, attempted to unify gravity and electromagnetism. None of them succeeded.

11 Tzou Kuo-Hsien, "*Champ vectoriel chargé de masse propre nulle*," *Comptes Rendus* 245 (1957): 289.

12 Gerald Feinberg, "Decays of the μ Meson in the Intermediate-Meson Theory," *Physical Review* 110, no. 6 (1958): 1482–1483, doi:10.1103/physrev.110.1482.

13 Sheldon Lee Glashow, "The Vector Meson in Elementary Particle Decays," PhD thesis (Harvard University, 1958).

14 Sheldon Lee Glashow, "Partial-Symmetries of Weak Interactions," *Nuclear Physics* 22, no. 4 (1961): 579–588, doi:10.1016/0029-5582(61)90469-2. See also an equivalent paper written over three years afterward: Abdus Salam and John Clive Ward, "Electromagnetic and Weak Interactions," *Physics Letters* 13, no. 2 (1964): 168–171, doi:10.1016/0031-9163(64)90711-5; the authors fail to cite my paper.

15 Jun John Sakurai, "Theory of Strong Interactions," *Annals of Physics* 11, no. 1 (1960): 1–48, doi:10.1016/0003-4916(60)90126-3.

to its five gauge bosons. Sakurai's close relationship with high energy physicists at Berkeley may have impelled them to search harder for such particles. Within a year, they found the isotopic triplet of p mesons at 750 MeV (million electron volts) and the singlet ω meson at 780 MeV, with even more vector mesons coming soon.

One year later, Murray Gell-Mann[16] and, independently, Yuval Ne'eman devised a generalization of Heisenberg's SU(2) isospin symmetry based on the larger group SU(3).[17] It became known as flavor SU(3). Murray, however, called it the eightfold way because it gathers low-spin mesons and baryons into octets of hadrons which would have been degenerate were the symmetry exact. Isospin is a more useful symmetry than flavor SU(3). Isotopic multiplets are split in mass by a few MeV, whereas members of the lightest hadron octets are split by hundreds of MeV.[18] Their symmetry scheme became widely accepted as an approximate global symmetry upon the discovery of the predicted omega-minus baryon in 1964. Its discovery completed the decimet of spin-3/2 baryons. The success of isospin symmetry is now known to result from the low masses of up and down quarks. Flavor SU(3) symmetry is much more broken than isospin symmetry because the strange quark is much heavier than its slender up and down cousins.

Later in 1961, Gell-Mann and I explored the possibility that all elementary particle interactions—strong, weak, and electromagnetic—arise from gauge theories: my electroweak theory together with gauged flavor SU(3).[19] We explained that flavor SU(3), which he had originally conceived as a global symmetry, could be promoted to a gauge symmetry, just as Sakurai had suggested for isospin symmetry. A complete nonet of vector mesons had been found. The ρ and ω mesons were joined by the singlet φ meson at 1020 MeV, and the doublet K^* along with their antiparticles at 895 MeV. These could be interpreted as the gauge particles of a badly broken SU(3) gauge theory. Our efforts led nowhere. We wrote:

> The model we have discussed is not seriously put forward as a physical theory, but it is a good illustration of the ideas involved in the gauge method. The fact that we were led to such an ugly model suggests … that we are missing some important ingredient of the theory.[20]

There were quite a number of missing ingredients, among them the quark model and charm. Even more important would be the notion of quark color, which provided an arena in which the strong interactions could act without interfering with electroweak gauge symmetry. We continued:

> We have discussed several ways in which the strong interactions may constitute a partially gauge-invariant theory [based on flavor SU(3)], and have sketched a formal gauge- invariant theory of the weak interactions [my electroweak SU(2) $\times$ U(1) gauge theory]. In general, the "weak" and "strong" gauge symmetries will not be mutually compatible… We have not attempted here to describe the three types of interaction together, but only to speculate about what the symmetry of each one might look like in an ideal limit where symmetry-breaking effects disappear.[21]

When we speak of symmetries of particle physics, we mean the transformations under which the Lagrangian remains unchanged. Symmetries may be usefully approximate when certain terms in the Lagrangian are small enough to be relatively inconsequential. For example, the quantum number called strangeness, or equivalently hypercharge, is rigorously conserved by the strong and electromagnetic interactions, but not by the weak interactions. This explains why strange particles, like kaons, are produced in pairs by the strong interactions, but exhibit long lifetimes. It is because their decay is governed by the weak interactions. Similarly, isospin is a useful symmetry because two of the quark flavors, up and down, have small masses compared to the strong interaction energy scale. Exact symmetries of the Lagrangian can also break spontaneously. This phenomenon was first described by Yoichiro Nambu in the context of condensed matter theory,[22] and in that same year by Jeffrey Goldstone for relativistic quantum field theories.[23]

Imagine a system of interacting scalar quantum fields whose interactions are invariant under a con-

[16] Murray Gell-Mann, "The Eightfold Way: A Theory of Strong Interaction Symmetry," California Institute of Technology, Synchrotron Lab Report 20 (1961), doi:10.2172/4008239.

[17] Yuval Ne'eman, "Derivation of Strong Interactions from a Gauge Invariance," *Nuclear Physics* 26, no. 2 (1961): 222–229, doi:10.1016/0029-5582(61)90134-1.

[18] Particle physicists often quote masses in energy units. The implied unit of mass is MeV/c^2. The widely split pseudoscalar meson octet comprises the pion isotriplet with rest energy 140 MeV, the strange kaon doublet and its antiparticles at 500 MeV, and the eta singlet at 550 MeV.

[19] Sheldon Lee Glashow and Murray Gell-Mann, "Gauge Theories of Vector Particles," *Annals of Physics* 15, no. 3 (1961): 437–460, doi:10.1016/0003-4916(61)90193-2, reproduced in *Selected Papers on Gauge Theory of Weak and Electromagnetic Interactions*, ed. Choi Heng Lai (Singapore: World Scientific, 1981), 68–91.

[20] Glashow and Gell-Mann, "Gauge Theories of Vector Particles," 90.

[21] Glashow and Gell-Mann, "Gauge Theories of Vector Particles," 90–91.

[22] Yoichiro Nambu, "Quasi-Particles and Gauge Invariance," *Physical Review* 117, no. 3 (1960), doi:10.1103/physrev.117.648.

[23] Jeffrey Goldstone, "Field Theories with Superconductor Solutions," *Il Nuovo Cimento* 19, no. 1 (1961): 154–164, doi:10.1007/bf02812722. In the spring of 1960, Goldstone and I occupied neighboring offices as postdocs at CERN. As he explored spontaneous symmetry breaking, I was completing my electroweak paper. Sadly, neither of us was much interested in what the other was doing.

tinuous group. The simplest example is a single complex field $\varphi = \varphi_1 + i\varphi_2$ whose interaction potential depends only on $|\varphi|$, its magnitude. The system is invariant under a U(1) group corresponding to changes in φ's complex phase. For certain choices of the potential, the symmetry breaks spontaneously. One real field becomes a massless Goldstone boson while the other remains massive. More generally, when a continuous global symmetry spontaneously breaks, one Goldstone boson appears for each generator of the group that breaks, while at least one massive boson necessarily survives. Because no such massless particles are known to exist, Goldstone's bosons might seem to be useless artifacts of formal quantum field theory. But in the presence of explicit but small symmetry-breaking terms, spontaneous symmetry breaking will yield pseudo-Goldstone bosons that typically have small masses. Pions, which are the lightest hadrons, are usefully regarded as pseudo-Goldstone particles associated with chiral symmetry breaking. Other pseudo-Goldstone bosons, such as phonons, magnons, and Nambu's quasiparticles, play important roles in the theory of condensed matter.

The year 1964 was fabulously fruitful for fundamental physics. At least seven seminal developments took place.

1. *The Invention of Quarks:* Fractionally charged constituents of hadrons were proposed independently by Gell-Mann, George Zweig, and André Petermann.[24] Gell-Mann called his hypothetical particles quarks, Zweig called them aces, and Petermann said of them:

   > *Ou bien, si l'on veut préserver la conservation de la charge, ce qui est hautement souhaitable, les particules doivent alors avoir des valeurs non entières de la charge. Ce fait est déplaisant mais ne peut, après tout, être exclu sur des bases physiques.*[25]

   Originally, there were to be three quark flavors: up, down, and strange, with electric charges of 2/3, −1/3, and −1/3, respectively, in units wherein the proton charge is one. Up and down quarks have small masses and are the constituents of nucleons; strange quarks, which are found in so-called strange particles, are considerably heavier. Baryons are made of three quarks, antibaryons of three antiquarks, and mesons of one quark and one antiquark. Neither quarks nor antiquarks nor the gluons that hold them together can be isolated from the hadrons they form.
2. *Enter the Ω^- Baryon:* Earlier I mentioned the discovery of Gell-Mann's predicted omega-minus baryon. Its production and decay were first observed within a bubble chamber by Nicholas Samios's group at Brookhaven National Laboratory.[26] The new particle displayed just the properties Gell-Mann had predicted, including its mass, spin, electric charge, lifetime, and decay modes.

   The discovery convinced many formerly reluctant particle physicists of the relevance of quarks and the eightfold way, thereby enabling me to collect on several wagers I had made with my more staid colleagues.
3. *A Fourth Quark Is Proposed*: Gell-Mann introduced only three quark flavors because three were sufficient to describe all then-known hadrons. Nonetheless, James ("BJ") Bjorken and I proposed that there should exist an additional fourth quark flavor which we dubbed *charm*.[27] With the charmed quark charge chosen to be 2/3, the quarks would comprise weak two doublets, just like the known leptons, thereby realizing a long dreamt of symmetry between leptons and hadrons.[28] Shamefully, neither Bjorken nor I recognized that a weak current including the charmed quark could expunge the dreaded strangeness-changing neutral currents that beset the electroweak model. Much later, two additional quark flavors were found, forming a third quark doublet. These quarks, called top and bottom, are considerably more massive than the others. An additional charged lepton was discovered as well. These (electrons, muons, and the tau lepton) along with their three neutrinos comprise three lepton doublets. Quark- lepton symmetry was restored.

[24] Murray Gell-Mann, "A Schematic Model of Mesons and Baryons," *Physics Letters* 8, no. 3 (1964): 214–215, doi:10.1016/s0031-9163(64)92001-3; received January 4, 1964; George Zweig, "An SU(3) Model for Strong Interaction Symmetry and Its Breaking: Version 2," CERN-TH-412 (February 1964); Andre Petermann, "*Propriétés de l'étrangeté et uneformule de masse pour les mésons vectoriels*," *Nuclear Physics* 63, no. 2 (1965): 349–352, doi:10.1016/0029-5582(65)90348-2; received December 30, 1963.

[25] Petermann, "*Propriétés de l'étrangeté*," 351. English translation: "Or, if charge retention is to be preserved, which is highly desirable, then the particles must have non-integer charge values. This fact is unpleasant but it cannot be excluded on physical grounds."

[26] Virgil Barnes et al., "Confirmation of the Existence of the Ω^- Hyperon," *Physics Letters* 12, no. 2 (1964): 134–136, doi:10.1016/0031-9163(64)91137-0.

[27] James Bjorken and Sheldon Lee Glashow, "Elementary Particles and SU(4)," *Physics Letters* 11, no. 3 (1964): 255–257, doi:10.1016/0031-9163(64)90433-0. See also Yasuo Hara, "Unitary Triplets and the Eightfold Way" *Physical Review* 134, no. 3B (1964): 701–704, doi:10.1103/physrev.134.b701.

[28] Augusto Gamba, Robert Marshak, and Susumu Okubo, "On a Symmetry in Weak Interactions," *Proceedings of the National Academy of Sciences* 45, no. 6 (1959): 881–885, doi:10.1073/pnas.45.6.881.

4. *CP Symmetry Is Violated:* In the 1950s, physicists showed that weak interactions violate both space reflection P and charge conjugation C. It was hoped that the combined operation CP remained an exact symmetry. It does not. In 1964, the Fitch-Cronin group at Princeton observed the rare decay of long-lived neutral kaons into two pions, a decay mode forbidden by CP invariance.[29] Since then, CP violation has been observed in the decay of strange baryons as well as that of mesons containing either charmed or bottom quarks. Accommodating CP violation within the original two-family standard model proved to be very difficult, but in 1973, two Japanese physicists showed that CP can easily be violated in a world with six quarks.[30] They thereby earned themselves Nobel Prizes.
5. *The Higgs Mechanism Is Devised*: What would happen if spontaneous symmetry breaking were to take place in a gauge theory? The question was addressed by three different collaborations in the autumn of the second annus mirabilis of the twentieth century. Their articles were published in the same volume of the same journal![31] If a group of gauge symmetries is unbroken, each of its generators is associated with a massless gauge boson. Suppose that the gauge bosons are coupled to a multiplet of scalar bosons whose potential is such the symmetry group spontaneously breaks. In this case, no massless Goldstone bosons appear. Instead, each of the gauge bosons associated with a broken symmetry acquires mass. The spontaneous breakdown of a global symmetry yields a massless Goldstone boson, while the spontaneous breakdown of a local symmetry yields a massive gauge boson. This process could have been called the Brout-Englert- Higgs-Guralnik-Hagen-Kibble mechanism. Instead, mercifully, it is called the Higgs mechanism. The scalar bosons that survive symmetry breaking are just the Higgs bosons. Several years later, Steven Weinberg made brilliant use of the Higgs mechanism by inserting it into my electroweak model to break the SU(2) $\times$ U(1) electroweak symmetry. He introduced a complex doublet of spinless bosons with electroweak couplings. Their potential energy is chosen so that the gauge symmetry breaks down. Three of the four gauge bosons, $W^{\pm}$, and Z^0 acquire mass, while the photon remains massless. One scalar Higgs boson survives symmetry breaking and serves as the agent providing mass to the weak intermediaries, and, as well, to quarks and charged leptons. In the hands of my high-school buddy, my model was transformed into a genuine theory![32]
At this point, electroweak theory was only a theory of leptons. It could not be extended to describe the weak interactions of quarks until the problem of strangeness-changing neutral currents was solved. The GIM (Glashow- Iliopoulos-Maiani) mechanism would perform this task.[33] I offer a brief and cryptic explanation of what John Iliopoulos, Luciano Maiani, and I did. Prior to our work, the hadronic weak interactions resulted from a hadronic current wherein the up quark couples to a particular linear combination of the two $Q = -1/3$ quarks: $d\cos\theta + s\sin\theta$. We simply provided an additional weak coupling of the then-hypothetical charmed quark to the orthogonal combination of quarks: $s\cos\theta - d\sin\theta$. As an immediate consequence, the neutral current conserves strangeness and the problem is solved. What could be simpler?
6. *Quarks Become Colored and Quantum Chromodynamics Is Born:* Oscar Greenberg set out to solve a vexing problem with the quark model having to do with statistics. Quarks and leptons are spin-1/2 fermions whose wavefunction must be antisymmetric under particle interchange. Mesons have integer spin and are bosons. Their wave functions must be symmetric. However, the quark wavefunction within baryons had to be symmetric in both space and spin. To fix this, Greenberg appealed to the obscure notion of "parafermions of order 3."[34] Some years later, his

[29] James Christenson et al., "Evidence for the 2π Decay of the K_2^0 Meson," *Physics Letters* 13, no. 4 (1964): 138–140, doi:10.1103/physrevlett.13.138.

[30] Makoto Koshiba and Toshihide Maskawa, "CP-Violation in the Renormalizable Theory of Weak Interaction," *Progress of Theoretical Physics* 49, no. 2 (1973): 652–657, doi:10.1143/ptp.49.652.

[31] Peter Higgs, "Broken Symmetries and the Masses of Gauge Bosons," *Physical Review Letters* 13, no. 16 (1964): 508–509, doi:10.1103/physrevlett.13.508. Peter Higgs, "Broken Symmetries, Massless Particles, and Gauge Fields," *Physical Review Letters* 12, no. 2 (1964): 132–133, doi:10.1016/0031-9163(64)91136-9. François Englert and Robert Brout, "Broken Symmetry and the Mass of Gauge Vector Mesons," *Physical Review Letters* 13, no. 9 (1964): 321–323, doi:10.1103/physrevlett.13.321. Gerald Guralnik, Carl Hagen, and Tom Kibble, "Global Conservation Laws and Massless Particles," *Physical Review Letters* 13, no. 20 (1964): 585–587, doi:10.1103/PhysRevLett.13.585.

[32] Steven Weinberg, "A Model of Leptons," *Physical Review Letters* 19, no. 21 (1967): 1264–1266, doi:10.1103/physrevlett.19.1264. See also Abdus Salam, "The Standard Model," in *Elementary Particle Theory: Relativistic Groups and Analyticity*, ed. Nils Svartholm (Stockholm: Almqvist and Wiksell, 1968).

[33] Sheldon Lee Glashow, John Iliopoulos, and Luciano Maiani, "Weak Interactions with Lepton-Hadron Symmetry," *Physical Review D* 2, no. 7 (1970): 1285–1292, doi:10.1103/physrevd.2.1285.

[34] Oscar Greenberg, "Spin and Unitary-Spin Independence in

notion was reconfigured in terms of quark color. Each quark flavor comes in three different colors, color acting simply as a new quantum number. Quark color has nothing to do with vision, just as quark flavor has nothing to do with taste. Every baryon contains one quark of each color, and the antisymmetry of its wave function is relegated to the arena of color. The statistics problem was solved. Even more importantly, quark color provided the arena in which strong interactions could operate without disturbing the electroweak symmetry. In the early 1970s, today's successful gauge theory of the strong force emerged.[35] Quantum chromodynamics (QCD) is the unbroken SU(3) gauge theory underlying strong interactions, just as quantum electrodynamics (QED) is the unbroken U(1) gauge theory underlying electromagnetic interactions. Its massless gauge bosons are the eight gluons. Unlike photons, colored gluons—like colored quarks, the particles they act upon—cannot exist as isolated particles. This consequence of QCD is called color confinement, and has been more or less established theoretically and through sophisticated computer simulations. The QCD force binding quarks to form hadrons results from the exchange of colored gluons between colored quarks, while the nuclear force between colorless nucleons arises as a pale remnant of QCD. Analogously, the electric force binding charged electrons to charged nuclei to form atoms results from the exchange of photons, while the chemical force between electrically neutral atoms arises as a pale remnant of QED.

7. *The Cosmic Microwave Background Is Seen:* The dramatic and serendipitous tale of the discovery of the remnant radiation from the Big Bang has little or nothing to do with the Yang-Mills model or gauge theories, but it was certainly the most significant scientific achievement of 1964. The discovery has enabled cosmology to emerge as an exact, quantitative scientific discipline. Arno Penzias and Robert Wilson announced their results on May 20, 1964. Their article was published the next year.[36]

The Standard Model of particle physics is a gauge theory based on the semisimple (three-component) Lie group SU(3) × SU(2) × U(1). It offers a seemingly correct and complete description of virtually all elementary particle phenomena. Its SU(3) component yields the unbroken gauge theory of quantum chromodynamics, which ensures quark confinement and underlies nuclear forces. The SU(2) × U(1) is spontaneously broken. Its broken symmetries yield the massive mediators to weak interactions; its unbroken U(1) subgroup yields quantum electrodynamics. Using three simple groups to describe three different interactions (weak, strong, and electromagnetic), the Standard Model is not a unified theory. A more ambitious theory would embed it within a larger one-component group, what mathematicians call a simple group. Howard Georgi and I proposed just such a theory based on the simple group SU(5).[37] Neither it nor any other so-called grand unified theory has yet proven empirically successful.

In 1967, Abdus Salam had expressed confidence that the electroweak theory was renormalizable. I myself had falsely and famously made such a claim. But it was Martinus Veltman and his student Gerard't Hooft who would establish the renormalizability of the electroweak theory.[38] In 1971, theoretical physicists were delighted when't Hooft announced his result. The popularity of the electroweak theory exploded. A further technical problem involved the possible appearance of so-called Adler anomalies in the Standard Model. Fortunately, the theory was shown to be anomaly free.[39] With its theoretical credentials firmly established, a number of vexing experimental questions arose. They would be answered… in time.

Where were the predicted neutral current phenomena? Strongly motivated by the work of't Hooft and Veltman, experimenters both in the United States and Europe competed to detect neutral current interactions. They were first seen in 1973 at CERN, and

a Paraquark Model of Baryons and Mesons," *Physical Review Letters* 13, no. 20 (1964), doi:10.1103/physrevlett.13.598.

[35] E.g., Harald Fritzsch, Murray Gell-Mann, and Heinrich Leutwyler, "Advantages of the Color Octet Gluon Picture," *Physics Letters B* 47, no. 4 (1973): 365–368, doi:10.1016/0370-2693(73)90625-4; David Gross and Frank Wilczek, "Ultraviolet Behavior of Non-Abelian Gauge Theory," *Physical Review Letters* 30, no. 26 (1973): 1343–1346, doi:10.1103/physrevlett.30.1343; H. David Politzer, "Reliable Perturbative Results for Strong Interactions?" *Physical Review Letters* 30, no. 26 (1973): 1346–1349, doi:10.1103/physrevlett.30.1346.

[36] Arno Penzias and Robert Wilson, "A Measurement of Excess Antenna Temperature at 4080 Mc/s," *Astrophysics Journal* 142 (1965): 419–421, doi:10.1086/148307.

[37] Howard Georgi and Sheldon Lee Glashow, "Unity of All Elementary-Particle Forces," *Physical Review Letters* 32, no. 8 (1974): 438–441, doi:10.1103/physrevlett.32.438.

[38] Gerard't Hooft, "Renormalizable Lagrangians for Massive Yang-Mills Fields," *Nuclear Physics B* 35, no. 1 (1971): 167–188, doi:10.1016/0550-3213(71)90139-8. Gerard't Hooft: and Martinus Veltman, "Regularization and Renormalization of Gauge Fields," *Nuclear Physics B* 44, no. 1 (1972): 189–213, doi:10.1016/0550-3213(72)90279-9.

[39] Claude Bouchiat, John Iliopoulos, and Philippe Meyer, "An Anomaly-Free Version of Weinberg's Model," *Physics Letters B* 38, no. 7 (1972): 519–523, doi:10.1016/0370-2693(72)90532-1.

soon afterward at Fermilab, near Chicago.[40] Careful studies of both charged current and neutral current interactions would provide additional credence for the quark constituency of hadrons.

Where were the particles containing charmed quarks? On November 11, 1974, two collaborations, located at opposite coasts of the United States, reported the discovery of new spin-one meson at an energy of 3.1 GeV.[41] Its unexpectedly long lifetime convinced my colleague Álvaro de Rújula and me that the new particle was a bound state of a charmed quark and its antiquark.[42] De Rújula dubbed it *charmonium*, after positronium, which is the bound state of an electron and its antiparticle. Others called it the J/Psi particle. Not so soon afterward, hadrons containing just one quark or antiquark (charmed particles) were detected. By that time, evidence had been found for the existence of an unexpected fifth quark, rapidly dubbed the bottom quark in anticipation of a sixth, top quark.

Where were the weak intermediaries $W^{\pm}$ and Z^0? Thanks to the ingenuity of the experimental physicist Carlo Rubbia and the engineer Simon van der Meer, the CERN collider was made capable of producing these particles. They were both observed in 1983 at CERN by two collaborative experiments.[43] The properties of these particles agreed with expectations from the electroweak theory.

The bottom quark was discovered in 1977, but where was the top quark? It took physicists over a decade to accept my suggestion of a fourth quark to establish quark-lepton symmetry. Yet, upon the discovery of the bottom quark, everyone immediately agreed that a sixth quark had to exist as well. Nature was not cooperative. The top quark was so massive that experimenters had to struggle for almost two decades before it could be produced and detected. The top quark was discovered simultaneously by two collaborations working at Fermilab in 1995.[44] Its mass is about 173 GeV, 137 times greater than that of the charmed quark. The number 137 is the inverse of the fine structure constant and had an almost magical significance for both Arthur Eddington and Wolfgang Pauli, perhaps because it is also the gematrial equivalent of Kabbalah.

Where was the Higgs boson, the last ingredient of the Standard Model? After decades of searching, the discovery of a particle that seems likely to be the Higgs boson was announced on July 4, 2012, but in Europe, not the United States. It was observed at CERN, again by two collaborations.[45] Its mass is about 125 GeV, a value that leads to a serious theoretical problem, which I have neither the time nor space to describe.

Why should there be three similar families of quarks and leptons? Why do these particles have such peculiar and seemingly patternless masses? What mechanism is responsible for the tiny masses of neutrinos? These and many others are questions we cannot yet answer, which makes this a sensible point for me to conclude my tale.

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[41] Jean-Jacques Aubert et al., "Experimental Observation of a Heavy Particle *J*," *Physical Review Letters* 33, no. 23 (1974): 1404–1406, doi:10.1103/physrevlett.33.1404. Jean-Eudes Augustin et al., "Discovery of a Narrow Resonance in e^+e^- Annihilation," *Physical Review Letters* 33, no. 23 (1974): 1406–1408, doi:10.1103/PhysRevLett.33.1406.

[42] Álvaro de Rújula and Sheldon Lee Glashow, "Is Bound Charm Found?" *Physical Review Letters* 34, no. 1 (1): 46–49, doi:10.1103/physrevlett.34.46.

[43] UA1 Collaboration: Geoffrey Arnison et al., "Experimental Observation of Isolated Large Transverse Energy Electrons with Associated Missing Energy at s=540GeV" *Physics Letters B* 122, no. 1 (1983): 103–116, doi:10.1016/0370-2693(83)91177-2. UA1 Collaboration: Geoffrey Arnison et al., "Experimental Observation of Lepton Pairs of Invariant Mass around 95 GeV/c^2 at the CERN SPS Collider," *Physics Letters B* 126, no. 5 (1983): 398–410, doi:10.1016/0370-2693(83)90188-0. UA2 Collaboration: Marcel Banner et al., "Observation of Single Isolated Electrons of High Transverse Momentum in Events with Missing Transverse Energy at the CERN pp Collider," *Physics Letters* 122, no. 5–6 (1983): 476–485, doi:10.1016/0370-2693(83)91605-2. UA2 Collaboration: Paolo Bagnaia et al., "Evidence for $Z^0 \to e^+e^-$ at the CERN pp Collider," *Physics Letters B* 129, no. 1–2 (1983): 130–140, doi:10.1016/0370-2693(83)90744-X.

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