The Infinity Puzzle: Quantum Field Theory and the Hunt for an Orderly Universe

Reviewed by Brian E. Blank

**The Infinity Puzzle: Quantum Field Theory
and the Hunt for an Orderly Universe**

Frank Close

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The first quantum field theory (QFT), quantum electrodynamics (QED), originated in Paul Dirac's 1927 paper concerning the emission and absorption of radiation. Although Dirac's work describing the electromagnetic force was the logical sequel to a brief but intense development of the new quantum theory, it promptly gave rise to seemingly insurmountable difficulties. In a letter written in February 1928, Wolfgang Pauli suggested to Dirac that a fundamental change in perspective would likely be needed. Working with Werner Heisenberg, Pauli had calculated the self-energy of a single electron interacting with its own electromagnetic field. The value, they were chagrined to learn, turned out to be infinite. "What do you think about this?" Pauli challenged.

During the 1930s, QFT was the instrument for important developments such as Enrico Fermi's theory of beta decay (1934) and, at the end of the decade, Pauli's derivation of the connection between spin, Bose-Einstein statistics, and Fermi-Dirac statistics. Despite such successes, physicists remained disturbed by the divergent integrals that arose when many basic physical quantities were calculated. Rather than being explained, the infinities proliferated as the particle zoo expanded. "New divergence sorrows" were the words with

which Hendrik Kramers mentioned the meson theory of nuclear forces at the 1947 Shelter Island conference devoted to quantum physics.

The title of Frank Close's new book, *The Infinity Puzzle*, is the author's metaphor for the forty-five-year struggle to formulate quantum field theories in which the calculations can be made meaningful even when they involve divergent integrals. Although the task of explaining the mathematical conundrums of sophisticated physical theories to a reader who is not assumed to know calculus might seem daunting or even quixotic, Close has the expertise and experience to attempt it: not only is he a theoretical physicist at Oxford with a background in particle physics that includes stints at the Stanford Linear Accelerator Center (SLAC) and at CERN, he is also a prolific author who specializes in explaining physics to the lay person. Some fifteen years ago, he was awarded the Kelvin Medal for "outstanding contributions to the public understanding of physics."

The subtitle of *The Infinity Puzzle* relates QFT to the hunt for an orderly universe. Paradoxically, the union of quantum theory and special relativity seems to portend anything but order. According to the Uncertainty Principle of quantum mechanics, highly erratic fluctuations of energy occur over small intervals of time. According to the theory of special relativity, these vacillations in energy result in the creation and annihilation of mass. As a result, the vacuum in QFT is no simple void: it teems with bits of matter so ephemeral that they are called *virtual particles*. To model such phenomena, a quantum field is not taken to be the garden variety vector field of classical electrodynamics, but an operator-valued map on space-time. The reigning theories of quantum fields are the electroweak theory (EWT), which is the unified framework for the electromagnetic force and the

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weak force, and quantum chromodynamics (QCD), the framework for the strong force. Close prefers the arcane term *quantum flavordynamics* (QFD) to EWT. The first two times he refers to QFD (p. 255 and p. 258), his wording may lead a reader to the understanding that QFD is a theory of the weak force, which is in agreement with a standard text on particle physics [4, p. 55]. Thereafter, Close uses QFD to signify the theory of the combined weak and electromagnetic forces, in agreement with the meaning he gives in his glossary.

The first three chapters of *The Infinity Puzzle* are devoted to QED. Close begins his discussion with effective, qualitative explanations of self-energy and vacuum polarization, the two basic sources of divergent integrals. These mathematical malignancies would eventually be cured by *renormalization* theory, the first hints of which appeared in the 1930s in the work of Heisenberg, Victor Weisskopf, and, especially, Kramers, who promoted the renormalization process at the Shelter Island conference. Renormalization began with the realization that the “bare” quantities appearing in the formulas of QFT were theoretical, unphysical parameters. The first step was to assign them values based on observable, physical quantities. For example, the electron’s physical mass m is equal to its bare mass m_0 augmented by m_{QF} , the infinite mass that the electron acquires by interacting with its magnetic field and the vacuum. If m_0 is allowed to have some finite value, as intuition suggests, then the left side of the equation $m = m_0 + m_{\text{QF}}$ has a finite, experimentally measured value, whereas the right side is infinite. Instead, the bare mass, which cannot be measured, is assigned an infinite value by the equation $m_0 = m - m_{\text{QF}}$. In the renormalization calculus, the infinities of m_0 and m_{QF} cancel, resulting in the same finite observed value on both sides of the equation $m = m_0 + m_{\text{QF}}$.

Granting that this arithmetic can be made sensible, we are left with two questions. By transferring the infinity from m to m_0 (and carrying out a similar shell game for charge), can we eliminate all the infinities of QED? And if we change the length scale of our measurement of m , that is, if we change the depth to which we probe the cloud of virtual particles surrounding the electron, thereby obtaining a different observed value for m , does our theory remain consistent? Using a toy multiplicative renormalization, Close answers this way: “The key discovery was that whatever you calculated, the way that infinity emerged from the mathematics was the same from one process to the next. For example, when physicists calculated one quantity, they found a horrible infinite thing....Then they calculated some other quantity and found the very same horrible infinite thing,

but this time multiplied by, let’s suppose 2....If an experiment had already measured the true (finite!) value for the first quantity, QED could then confidently predict the magnitude of the second as being twice as great.” Close does caution that the actual process of renormalization is a delicate mathematical technique: “So finely balanced are the infinities that extracting finite numbers by canceling them is like walking a tightrope over Niagara Falls.”

Renormalization theory not only received advocacy at the Shelter Island conference, it also found an important numerical test. It was at Shelter Island that Willis Lamb reported his measurement of a minute energy difference between the $2S_{1/2}$ and $2P_{1/2}$ levels of a hydrogen atom, a shift resulting from the vacuum fluctuations predicted by QED. On the train ride back from the conference, Hans Bethe used a primitive form of renormalization to derive an approximation to the Lamb shift. By April 1948, Richard Feynman, Julian Schwinger, and Sin-itiro Tomonaga had, independently, developed more sophisticated techniques to handle the divergent integrals of QED. In 1949, Freeman Dyson demonstrated that their theories were essentially equivalent. He also obtained renormalizability criteria that could be applied to field theories other than QED.

The modern slant on renormalization is that existing field theories are low-energy approximations of more comprehensive physical laws yet to be determined. Because there are presumably limits beyond which the current theories are inapplicable, the integrations of QFT are now performed with unspecified cutoffs. This strategy changes the shell game. Although the cutoffs prevent the divergences, the finite values of the resulting proper integrals depend on the cutoffs. The job of renormalization is to formulate a computational scheme in which the calculated quantities of QFT lose these dependencies when the observable parameters of the theory are assigned measured values. These ideas are appropriately relegated to a brief endnote in *The Infinity Puzzle*. (An entertaining explication of this approach can be found in Zee’s textbook [7, pp. 145–153]. A treatment at a mathematical level that splits the difference between Close and Zee is provided by [6].)

The success of renormalization in QED did not directly carry over to the weak and strong forces, which had their own divergence issues. The immediate obstacle was that the physics of nuclear interactions was poorly understood in the 1950s. In 1951, Paul Matthews and Abdus Salam devised a renormalizable theory of the strong interaction. Although their theory was correct according to the facts known at the time, it was refuted three years later by the detection

of a new particle—the strongly interacting, or hadronic, Delta baryon—in a University of Chicago cyclotron. The manner in which Close relates this episode illustrates the puzzling juxtapositions that sometimes occur in the torrent of information he effuses. Whereas Matthews and Salam, Close tells us, “thought that they had explained the whole strong force, discoveries soon showed that they had mapped but a mere corner of a vast land.” The immediate continuation is a paragraph that mentions the discovery of “strange particles” and muons in cosmic rays. The muon, which does not feel the strong force, had no role in undermining the Matthews-Salam theory. It is only after this interposition that Close comes to the Delta particle.

Without mathematics it is inevitable that a reader will gain only a murky notion of a quantum field and a still murkier notion of the field’s gauge transformations and symmetries. Having both hands tied behind his back, Close resorts to analogies. As examples of invariants, he uses the message conveyed by his book, which is the same whether it is read in English or in translation, and the duration of a transatlantic flight, which is the same whether the measuring watch is set to the time zone of departure or arrival. Analogies are helpful, and Close, like many other physicists, is good at finding them. Nevertheless, he seems to have sensed that the gauges and invariances of QFT will be nebulous to his readers. Adopting a time-honored method for communicating with a person who speaks a different language, Close turns to repetition. Once on each of pages 79, 81, 84, 108, and 113 and twice in one paragraph on page 85, he recounts an observation that Schwinger made at Shelter Island: gauge invariance implies both the existence of the electromagnetic interaction and the masslessness of its carrier, the photon. The emphasis Close places on mass in these pages foreshadows the key role it will soon assume in his story of QFT.

In a gauge theory, interactions among elementary particles are mediated by the exchange of particles, which are often virtual, known as *gauge bosons*. The photon is the gauge boson of the electromagnetic force. In general, whether a particle is fundamental or composite, it possesses a property known as *spin*, which is measured in integer multiples of $1/2$, the unit $\hbar$ being omitted or set equal to 1. By the Spin-Statistics Theorem mentioned earlier, bosons, the particles that obey Bose-Einstein statistics, are the particles that have integral spin. Zero spin particles, such as pions, are known as *scalar bosons*. A spin 1 particle, such as the photon, is called a *vector boson*.

Inspired by Schwinger’s insight, Chen-Ning Yang and Robert Mills developed a gauge invariant

theory of nucleons in 1953. However, because their theory predicted that the strong force is carried by massless charged bosons, particles that do not exist, it was dismissed as a failure even before its publication. Indeed, a graduate student of Salam, Ronald Shaw, who formulated Yang-Mills theory independently, elected to let his work rest unpublished in his Cambridge dissertation. In the rare instances in which Shaw is not entirely ignored, he receives only passing notice: among the references for this review, a line in [1], a footnote in [5]. Close’s effort at publicizing Shaw’s contribution is therefore welcome, but he is not persuasive when he refers to Shaw’s priority on the basis of Shaw’s private discussions with Salam in January 1954, one month before Yang publicly launched Yang-Mills theory at a Princeton seminar chaired by J. Robert Oppenheimer, with Pauli in the audience to heckle. On page 88, Close has Pauli asking Yang, “What is the mass of these vector bosons?” However, on page 189, Close renders Pauli’s question from the floor as, “Where are these massless vector mesons?” Mesons are bosonic, so the inconsistency is one of paraphrase, not of physics. Nevertheless, an entry for “meson” in either the glossary or the index could have straightened this out for the nonspecialist reader.

In 1956, Schwinger postulated the existence of two charged, massive carriers of the weak force, the W^+ and W^- bosons. Suspecting the existence of a combined theory of the electromagnetic and weak forces, he instructed his thesis student, Sheldon Glashow, to investigate such a possibility. Glashow published a model of the electroweak force in 1961. His theory required a third hypothetical particle, the massive, neutral Z^0 boson, to mediate the weak force. In addition to the three W^+ , W^- , and Z^0 particles not yet known, each with massiveness not yet explained, Glashow’s electroweak theory relied on an interaction, the neutral weak current, not yet observed. He concluded that his model seemed to be “without decisive experimental consequence,” and it was largely ignored.

Close’s narrative is, for the most part, chronological. As his story unfolds, we become aware that some of the beliefs harbored by the theorists required correction. With the apparent necessity of massive weak force carriers, Schwinger, in 1962, reexamined his earlier reasoning that gauge invariance implies the masslessness of a gauge boson. It turns out, as we finally learn on page 147, that Schwinger’s principle, believed by many physicists to be the indubitable law expressed so frequently between pages 79 and 113 of *The Infinity Puzzle*, was merely an article of faith, not a mathematical implication. Finding that

his conclusions depended on a physical assumption he had made, Schwinger announced that, in general, “There is no such necessary implication.” In a paper that appeared in 1963, Philip Anderson provided empirical confirmation of Schwinger’s reassessment.

The recognition that gauge invariance can coexist with massive gauge bosons clarified the mass problem on one front, but papers of Yoichiro Nambu and Jeffrey Goldstone in 1960 and 1961 had already opened up a troubling second front. Their work showed that whatever the gauge bosons might be, whether massive or massless, the phenomenon of spontaneous symmetry breaking necessitates an additional boson that is massless and scalar. In the opinion of many physicists, the pion, a scalar boson that is massive but light, served as an acceptable approximation of the Nambu-Goldstone boson for the strong force. However, in the case of the weak force, the Nambu-Goldstone boson, because of its charge, would have been easily detected. And yet no such boson had ever been observed. As Philip Anderson remarked in his 1963 article, it seemed as if the expected zero-mass Yang-Mills gauge boson and the zero-mass Nambu-Goldstone boson were “capable of ‘cancelling each other out’ and leaving finite mass bosons only.”

A year after this suggestion of cancellation, a triangular number of physicists published three relativistic versions of Anderson’s mechanism for the creation of massive vector bosons: Peter Higgs, whose paper was received by *Physics Letters* in July 1964; François Englert and Robert Brout, whose paper, the first of the three, was received by *Physical Review Letters* in June 1964; and Gerald Guralnik, Carl Richard Hagen, and Thomas Kibble, whose paper was received by *Physical Review Letters* in October 1964. These papers set forth a process, now called the *Higgs mechanism*,¹ by which particles acquire mass. When applied to EWT, the idea is that, at sufficiently high energy, symmetry is unbroken and all gauge bosons are massless. When condensation causes the electroweak symmetry to become hidden, the $W^\pm$ and Z^0 bosons absorb (or “eat”) the Nambu-Goldstone bosons, acquiring mass in the process. Additionally, a massive scalar boson, known as the Higgs boson, emerges from the process. So many bosons! The massless particle to which this review refers as the Nambu-Goldstone boson is more frequently called the Goldstone boson. As Goldstone observed (and Close pinpoints), the equations of his 1961 paper

give rise to a second scalar boson, but “the other Goldstone boson,” as Close wryly describes it, is the *massive* particle now known as the Higgs boson.

In 1964, Salam and John Ward published a combined theory of the electromagnetic and weak forces that, like the one Glashow published in 1961, had $SU(2) \times U(1)$ as the gauge group. These attempts to model a unified electroweak force did not fully succeed, because they did not account for the contrast between the massive gauge bosons of the weak force and the massless gauge boson of the electromagnetic force. In 1967, Steven Weinberg found the desired unification by using the idea of spontaneous symmetry breaking to explain the mass asymmetry of the four electroweak gauge bosons. In 1968, half a year after Weinberg’s paper had appeared in print, Salam, writing without his previous coauthor Ward, incorporated spontaneous symmetry breaking into the Salam-Ward model and arrived somewhere near the same point as Weinberg, who alone had considered the masses of the $W^\pm$ and Z^0 bosons.

At the end of 1967, there was a viable model for a unified electroweak theory, but the Infinity Puzzle was not yet solved. Close’s statement on page 142 that “Salam and Weinberg would be invoking hidden symmetry as the panacea for solving the Infinity Puzzle in the case of the weak force” seems careless: perhaps he meant “mass problem” rather than “Infinity Puzzle”. In fact, having examined Salam’s notebooks and having interviewed Weinberg, Close reports that “Salam’s notebooks showed no signs that he made serious efforts, let alone any inroads toward solving the problem [of infinities]. Weinberg also tried and failed.” In particular, Weinberg’s 1967 paper asserts only that “The model may be renormalizable.” In his Nobel lecture, Weinberg attributed his lack of success to the choice of a gauge that made renormalizability “totally obscure” [5, p. 165].

Weinberg’s article has become the most cited paper in particle physics, and the number of citations is apparently growing rapidly: on page 197 Close mentions “more than 7,100 citations,” but on page 297 it is “more than 8,000.” Compare the eventual impact Weinberg’s work had with the attention it received in the years 1967–1970, when its citation score was 0,0,0,1. Everything changed in 1971, the year Gerard ‘t Hooft, then a doctoral student of Martinus Veltman, used mathematical techniques developed by Veltman to solve the Infinity Puzzle for EWT and prove the renormalizability of the Glashow-Salam-Weinberg $SU(2) \times U(1)$ model.

Contemporaneously with the evolution of EWT, physicists made substantial progress toward a renormalizable Yang-Mills theory of the strong

¹In view of the shared provenance of this mass mechanism, Close prefers to enclose Higgs’s mechanism in quotation marks. Higgs himself refers to the ABEGHHKtH mechanism, the tH referring to Gerard ‘t Hooft, who will make his appearance in this review momentarily.

force. In 1961, Murray Gell-Mann and, independently, Yuval Ne'eman proposed a scheme that organized hadrons into families on the basis of parity and spin. The "Eightfold Way", as Gell-Mann dubbed the classification, succeeded spectacularly in predicting the Ω^- baryon, which was detected in a bubble chamber at Brookhaven National Laboratory (BNL) in 1964. The realization that hadrons could be grouped according to a pattern that was both descriptive and predictive was a major step forward, but physicists sensed that there were too many hadrons for them all to be fundamental. In 1964, Gell-Mann and, independently, George Zweig explained SU(3) symmetry of the Eightfold Way by introducing a small number of fractionally charged building blocks which, when combined in certain pairs and triplets, would yield hadronic matter. These constituents, named quarks and antiquarks by Gell-Mann, remained entirely hypothetical until 1968, when a team at SLAC used James Bjorken's theory of deep inelastic scattering to demonstrate that nucleons have substructure.² Even then, the quark model presented a serious problem. Inside a nucleon, quarks seemed to act as free particles. However, in the deep inelastic scattering of electrons from nucleons, no free quark had ever been pried loose. This concern was resolved in 1973 when David Gross and Frank Wilczek, and, separately, David Politzer, demonstrated that a Yang-Mills theory can enjoy a property known as *asymptotic freedom*: in QCD, as distance becomes vanishingly small, so does the strong force. The analogy of an elastic band that holds quarks inside a hadron is sometimes made.

By the end of the 1970s, the Standard Model of elementary particles and their interactions was substantially complete. In the years that followed, experimental physicists used high-energy particle accelerators to detect the particles predicted by the Standard Model. The $W^\pm$ and Z^0 bosons, for example, were discovered in 1983. The Higgs boson, however, proved to be more elusive. Close devotes his last two chapters to CERN's Large Hadron Collider (LHC), the gargantuan proton-proton collider assembled at great cost in a twenty-seven kilometer ring tunneled under France and Switzerland near Geneva. All throughout his book, Close handles the crucial interplay between theory and experiment adroitly. As his story winds down, he

²Gell-Mann had postulated three quarks: up, down, and strange. The experiments at SLAC in 1967–1968 provided evidence for these quark flavors. In the 1970s, theorists completed the list of quarks with three additional flavors: charm, bottom, and top. The charm quark was discovered simultaneously at BNL and SLAC in 1974. The bottom and top quarks were discovered at Fermilab in 1977 and 1995, respectively.

turns his attention to a new component of high-energy physics: the political machinations needed to secure funding for the colossal new machines essential to experimental physics. That this important aspect of modern physics is actually a focus of *The Infinity Puzzle* can be seen from the subtitle of the edition published by Oxford University Press for sale in the United Kingdom: *How the Quest to Understand Quantum Field Theory Led to Extraordinary Science, High Politics, and the World's Most Expensive Experiment*. Along the way, Close brings up the sad history of the abandoned Superconducting Super Collider (SSC), fifteen miles of which had been hollowed out in Ellis County, Texas, before the project's cancellation in October 1993. In a few paragraphs and a long endnote, Close makes it seem as if the key to the demise of the SSC was the failure to secure a \$2 billion contribution from the Japanese and that this failure was somehow tied to President George H. W. Bush vomiting at a state banquet in Japan and President Clinton not enacting vehicle import concessions. Many factors influenced the termination of the SSC, among them congressional politics (with references to "quark-barrel projects"); vocal opposition from prominent physicists such as Philip Anderson, who argued that support for disciplines such as condensed matter physics would better serve the public; and a host of issues that may be summed up as *Zeitgeist*: concern over the national debt, which had ballooned thanks to a foreign war; a lack of confidence in big science thanks to an incapacitating problem with the Hubble Space Telescope's primary mirror; and a desire for an assured return on taxpayer investment thanks to the perceived aimlessness of the space program.³ Some will think that Close has shed new light on an old debacle. Others will think, "Phooey!"

In 1986, opponents of the SSC protested the imprudence of committing a large fortune—the projected expenditure would exceed \$11 billion by 1993—to the search for a particle that might not exist. Lobbyists countered by portraying the project as a no-lose proposition: it would either confirm the Higgs mechanism or expose a Higgsless mechanism. Close's valedictory assessment echoes their argument: "Either the Higgs Boson will be found...or the real explanation, a total surprise, will be revealed. Only nature now knows. Soon humans will too." His optimism appears to have been justified. On July 4, 2012, CERN

³Six weeks after the cancellation of the SSC, in December 1993, the Hubble Telescope's optical system was repaired in a servicing mission by Space Shuttle Endeavour. For further discussion of the cancellation of the SSC, including the role of the International Space Station, refer to Steven Weinberg's recent article, "The Crisis of Big Science" in *The New York Review of Books*, May 10, 2012.

announced the discovery of a scalar boson with mass around 125 GeV (about 133 protons) that is consistent with the Higgs boson. At the time of this writing, the exact nature of this newly discovered particle has not been determined. As the CERN announcement asks, “Are its properties as expected for the long-sought Higgs boson, the final missing ingredient in the Standard Model of particle physics? Or is it something more exotic?”

If the Higgs mechanism is confirmed, then the Nobel committee may be faced with a difficult decision. Although the six physicists who proposed the mechanism in 1964 were jointly awarded the 2010 J. J. Sakurai Prize for Theoretical Particle Physics, no more than three recipients can share a Nobel Prize.⁴ The Nobel committee has struggled with such a quandary in the past, and the resulting decisions form a thread that runs through *The Infinity Puzzle*. Close highlights the exclusions of Dyson, Ward, and Bjorken from the Nobel Prizes that were awarded for advances to which they made essential contributions. He also thoroughly investigates the inclusion of Salam, who shared the 1979 prize with Glashow and Weinberg.

The case against Salam is threefold: (1) he did not write his Nobel Prize-winning 1968 EWT paper until after he had seen Weinberg’s published article; (2) His paper, unlike Weinberg’s, did not relate the $W^\pm$ and Z^0 masses and so did not point the way to the confirmation of EWT by experiment; (3) his paper, having been slipped into the proceedings of a symposium, did not undergo peer review and was based on the 1964 Salam-Ward article, the publication of which was questionable because it merely duplicated a model Glashow had advanced three years earlier. The strongest case for Salam is the testimony of his occasional collaborator, Robert Delbourgo, who recalls having drawn Salam’s attention to Weinberg’s paper after his colleague had already given lectures on EWT at Imperial College London in 1967 ([2], [3, p. 219], and interviews quoted in *The Infinity Puzzle*). Close offers an even-handed analysis that allows his readers to reach their own conclusions. Some will agree with Salam’s biographer, Gordon Fraser, who complained, “Having assigned credit where he sees fit, Close also confiscates much of that accorded to Salam” (*CERN Courier*, January 25, 2012). Others may feel that Close is too diplomatic. Indeed, while an advance copy of *The Infinity Puzzle* was in circulation, one of the physicists Close interviewed Web-posted a manuscript that makes a decidedly more explicit call for the confiscation of credit [2].

⁴Robert Brout died in 2011 and is therefore ineligible for the Nobel Prize, which is awarded only to persons believed alive at the time of the announcement. C. R. Hagen, who was born in 1937, is the youngest of the five surviving members of “The Gang of Six”.

There are rather a lot of slips in *The Infinity Puzzle*. They are all inconsequential, but some are potentially confusing. On page 24, Balmer’s formula is expressed in terms of $1/m^2 - 1/n^2$, but in the accompanying endnote, the negative of this difference is used. Additionally, in the same discussion, the symbol m that denotes a quantum number in Balmer’s formula is also used to denote a mass. When Close tells us, “In 1912 Niels Bohr found the explanation courtesy of quantum theory. In quantum theory any particle can take on a wavelike character,” he seems to be saying that Bohr anticipated matter waves a decade before Louis-Victor de Broglie had his Nobel Prize-winning insight. A few pages later Close states that Pauli realized in 1929 that he would have to take into account the effects of antimatter. The problem here is that the effects Pauli confronted were not then known to be due to antimatter—it was not until 1931 that Dirac predicted the anti-electron (or positron, as it became known). Commenting on a remark Salam inserted into a 1971 paper, Close writes on page 224, “Salam is claiming priority [with Ward] for the $SU(2) \times U(1)$ model, which is justified.” What justification are we to understand, given that priority for the $SU(2) \times U(1)$ model belongs to Glashow? On page 112, Close informs us that Glashow was a Ph.D. student at Harvard, but on page 120 he writes, “Glashow’s thesis, in 1958, was not public knowledge outside Cal Tech.” After attributing the Z^0 boson to Glashow, Close groups it with W^+ and W^- as Schwinger’s “invisible instruments” (p. 313).

In field theory, if μ is a scale parameter and $g = g(\mu)$ is the “running” coupling constant of the interaction, then the beta function is defined by $\beta(g) = \partial g / \partial (\ln(\mu))$. In QED, as in most field theories, beta is positive. By contrast, in QCD asymptotic freedom is reflected by negative beta. It will be noted from its formula that β is a slope. When Close first mentions beta (p. 44), he misleadingly asserts that, “In QED the slope of beta is positive,” the reviewer having italicized the words that do not belong. Throughout the eighteen pages that Close devotes to the beta function of QCD, the terms “beta slope”, “slope for beta”, and “beta” are used interchangeably.

In an attempt to explain the alphanumeric asymmetries in the factors of $SU(2) \times U(1)$, Close tries, “Elie Cartan...classified mathematical groups, among which were a set known as the special unitary (hence ‘SU’) groups with size N , where N is any integer. The case $N = 1$ is just the collection of simple numbers. To a mathematician this is so ‘unspecial’ that it is classified simply as $U(1)$.” Readers of the *Notices* will guess for

themselves the meanings of the last two quoted sentences.

The index to the Oxford University Press edition of *The Infinity Puzzle* has 228 entries for “boson”. There would have been many more had the indexer been aware that gluons, mesons, and photons are bosonic. In the version of *The Infinity Puzzle* issued by Basic Books, which owns the publication rights outside the United Kingdom, there are only three index entries for “boson”. Two of these fall under the subentry “penguin analogy”. It is somehow instructive to note that the indexer, who overlooked *so* much, was charmed by Close’s amusing analogy: “Fermions...act like cuckoos. Bosons, by contrast, are like penguins.” The third index entry for “boson” is subindexed as “known bosons”. This misleading reference is to a figure that lists the gauge bosons but none of the other known bosons. Some bosons, such as the $W^\pm$ and Z^0 particles, do have their own index entries, but several other bosons, such as the σ -meson, the ϕ -meson, and the J/ψ particle, are not indexed at all. In both versions of *The Infinity Puzzle*, the index cannot be used to find the definition of “boson”: the endnotes amount to 12 percent of the book, but neither Basic Books nor Oxford University Press saw fit to index the important material therein.

Many texts already cover much of Close’s story. Of these works, *The Infinity Puzzle* might be compared with *The Second Creation* [1], a wonderful book cited frequently by Close. *The Infinity Puzzle* does not replace *The Second Creation*, but it is a welcome addition to be considered alongside its predecessor. Although the two books share the same core subject matter, namely, the physics that led to the formulation of the Standard Model, there are significant differences in detail. Whereas Crease and Mann, the authors of *The Second Creation*, are more comprehensive, starting their story with the discovery of radioactivity in 1896, the year before the electron was detected, Close, by focusing on QFT, begins his account in the late 1920s, by which time the electron, proton, and photon had been discovered and special relativity, the new quantum mechanics, and spin were proven physical theories. By way of compensation for the material he quickly skips over, Close offers a deeper treatment of topics such as the Higgs mechanism and the development of QCD. Both books rely on the first-hand testimony that the authors industriously procured: Crease and Mann interviewed some one hundred twenty-five physicists and Close interviewed or corresponded with about eighty.

Of course, Close has a trump card. When *The Second Creation* was written, lobbying for the SSC

was only just under way, the Large Electron-Positron Collider occupied the tunnel that now houses the LHC, and BNL’s director could say, “America is a place you *do* things” without fear of contradiction [1, p. 255]. Now, a quarter century later, CERN’s discovery of the long-awaited Higgs boson has been heralded on the front pages of newspapers around the world. *The Infinity Puzzle* is the most up-to-date resource for the layperson who wonders, Why all the fuss?

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