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Stick-Figure Realism: Conventions, Reification, and the Persistence of Feynman Diagrams, 1948–1964

Introduction: Conventions, Habits, and the Paths of Particles

It was June, 1961. The dozen or so theoretical particle physicists in attendance at the "Conference on Weak and Strong Interactions" sat patiently through the La Jolla heat as Geoffrey Chew strode confidently to the podium. The tall and athletic Chew, rumored to have considered a career in professional baseball instead of particle physics, was just then gaining momentum in his push for a break from quantum field theory, the reigning theoretical framework at the time. "So that there can be no misunderstanding of the position I am espousing," Chew began, "let me say at once that I believe the conventional association of fields with strongly interacting particles to be empty." "I have yet to see," he continued, "any aspect of strong interactions that is clarified by the field concept." Chew focused on the so-called strong interaction, a nuclear force between certain subatomic particles. The theory used by most theorists when grappling with the strong interactions, quantum field theory, simply left Chew cold: "I do not wish to assert (as does [Lev] Landau) that conventional field theory is necessarily wrong, but only that it is sterile with respect to the strong interactions and that, like an old soldier, it is destined not to die but just to fade away."[1]

Two years later, his war with quantum field theory in full swing, Chew delivered an updated status report in a lecture at Cambridge University. He explained that his new approach, dubbed *S*-matrix theory, was by then behaving just like a "new mistress," "full of mystery but correspondingly full of promise." In contrast stood the rival, quantum field theory. Previously cast as the dying and sterile "old soldier," it now appeared to Chew more like an "old mistress," "clawing and scratching to maintain her status, but her day is past."[2]

As he declared quantum field theory to be "sterile" and of passing status, Chew began to build his own theoretical approach, *S*-matrix theory, directly upon a scaffolding of Feynman diagrams. The diagrams had been developed by Richard Feynman just over a decade earlier for exclusive service in field-theory calculations; a generation of graduate students had learned in the interim how to use the diagrams in highly specific, rule-bound ways as aids to their calculations within quantum field theory. Yet now Chew and his many students and collaborators clung to Feynman diagrams while seeking to drive a wedge between them and the particular meanings these diagrams had previously held within quantum field theory. It is this curious move—a ploy to extract the visual tool from its place within a "sterile" theory and to reinvest these diagrams with newfound meaning and significance—that motivates this paper.

The peculiar persistence of Feynman diagrams offers historians an unusual window onto some functions of scientific illustrations. The visual nature of the contested tool, and the many competing appropriations with which it was saddled, invite comparison with several issues raised by art historians and art theorists about the construction of "realism" in depictions of the natural world. This paper explores Feynman diagrams' strange history during the middle decades of the twentieth century through the lens of this art-historical scholarship.

Ernst Gombrich and Nelson Goodman both concluded that "realism" in art, as exemplified by the Renaissance turn to linear perspective, remained merely one kind of *convention* for rendering images and could lay no claim to being an especially "accurate" or "natural" kind of representation of the world. Gombrich famously attacked the notion of an "innocent eye" that could passively depict the natural world on a canvas; instead, he insisted that the artist would "tend to see what he paints rather than to paint what he sees." Similarly, Gombrich reported that "the starting point of a visual record is not knowledge but a guess conditioned by habit and tradition."[3] Taking his cue from Gombrich, Nelson Goodman proceeded to even stronger conventionalist conclusions: "The 'natural' kinds are simply those we are in the habit of picking out for and labeling." For Goodman, "Realism is relative, determined by the system of representation standard for a given culture or person at a given time. . . . Realistic representation, in brief, depends not upon imitation or illusion or information but upon inculcation. . . . If representation is a matter of choice and correctness a matter of information, realism is a matter of habit."[4] On Goodman's telling, "realistic" representations constitute merely our own "inculcation" and "habit" of drawing pictures a certain way.

Gombrich has consistently shied away from what he sees as Goodman's "anything goes" relativism and has sought instead to place learning and the acquisition of skills at the forefront of any discussion of artistic conventions and genres. He wrote in 1960 that "the study of the metaphysics of art should always be supplemented by an analysis of its practice, notably the practice of teaching," explaining further that "all representations are grounded on schemata which the artist learns to use."[5] Twenty years later, Gombrich expanded upon these notions, arguing that it should be "ease of acquisition" of such representational skills and habits, rather than any formal "nature-convention" distinction, upon which we should focus attention.[6] Joel Snyder likewise chided Goodman, arguing that "to attribute this privileging [of "realistic modes of depiction"] to familiarity does not explain the habit, the ease with which we 'pick it up,' or its strength. We have all kinds of habits, some of which are easy to break and others of which are like second nature."[7] As W. J. T. Mitchell has emphasized as well, chalking everything up to "habit" says nothing about what makes certain habits special, lasting, or "realistic": "Rococo and mannerist painting, for instance, both employ stylistic and iconographic features that were 'standard' and 'familiar' in their time. . . . But neither style counted as 'realistic' in its own time."[8] While likely agreeing with Goodman that "realism" in art derives from conventions and not from some privileged, unmediated means of capturing the world "as it is," these critics all urge us to continue where Goodman left off, seeking out why only certain habits get accorded "realist" status while so many others do not. If realism arises always and only from habit, can we specify how and why some habits get singled out as realistic?

Within science studies, several people have likewise debated whether scientific diagrams and illustrations simply picture the world as it is or remain "social constructions." After Bruno Latour and Steve Woolgar highlighted the central importance of "inscriptions" to scientific work, others produced case studies to demonstrate the "constructed" nature of the diagrams: computer-enhanced images of quasars can no more claim to speak in an unmediated, direct way about the outside world than can Renaissance botanical woodcuts.[9] Though plausible, stopping here is like equating all forms of written expression, from Romantic poetry to the federal tax code, to "constructions." Like the art historians' responses to Goodman, our next task within "post-constructivist" science studies is to begin to distinguish between *kinds* of "constructions"; the means by which the constructions make sense for certain scientists at particular times and places; how they spread among large scientific and nonscientific communities; and how these "constructions" can nevertheless be put to *work* in many situations, generating new ideas or providing a heuristic scaffolding for others.[10]

Drawing on both the art theorists and this work from science studies, this paper addresses the tenacity of Feynman diagrams in the 1950s and 1960s, even as their original meanings and embedding within a particular theory were being challenged. Part of the explanation for physicists' persistent use of the diagrams *does* derive from pedagogical inculcation of the sort highlighted by Gombrich and Goodman. Yet, as Gombrich, Snyder, and Mitchell contend in their critiques of Goodman, appeals to "habit" or "inculcation" alone do little to explain the physicists' continued reliance upon *these particular* representational tools and not others at this time. Some physicists interpreted Feynman diagrams as capturing *reality* more directly or completely than other visual tools did, regardless of how standard, familiar, or easy to use the other tools were. Attributions of "realism" for these physicists, then, did not stick to all diagrammatic "habits" equally. Feynman diagrams held, for this community at this time, certain "realist" associations not shared by other habit-forming, diagrammatic tools. The strength with which many physicists clung to Feynman diagrams, during this period of theoretical debate and uncertainty, therefore may have derived from these specifically "realist" (and not merely "habitual") associations.

The next section of the paper introduces briefly some uses of Feynman diagrams within both quantum field theory and the *S*-matrix program, the "old" and "new mistresses" of Chew's lecture. This sketch reveals that strange things were done with Feynman diagrams, well beyond their original meanings and uses. The next three sections then place these diagrams within larger visual traditions, to try to explain why the diagrams remained on theorists' blackboards and in their students' problem sets even as other pieces of their theories came and went.

Feynman Diagrams in Quantum Field Theory and *S*-Matrix Theory

In late March 1948, twenty-eight young theoretical physicists were gathered into the seclusion of a rural Pennsylvania hotel. Their mission, coming close on the heels of their return from war work, was to find a cure for a theory whose sickness had been plain for nearly two decades. By the early 1930s, it had already become clear that the physicists' scheme for treating the simplest of all fundamental interactions, the coupling of electrons and photons that we see as electromagnetism, could not be trusted with detailed calculations: in fact, in nearly every application of quantum electrodynamics, the theory produced unphysical infinities instead of finite numbers. Despite much work throughout the intervening years, physicists remained handicapped, unable to produce sensible predictions or descriptions. The organizers of this elite conference hoped that this second annual retreat would help nudge the new crop of theorists in the right direction.[11]

Among the several presentations delivered behind the closed doors of the Pocono Manor was a lecture by the young American theorist, Richard Feynman. Feynman drew simple stick-figure line drawings on the blackboard and explained how these diagrams could be used as a mnemonic device when wading through the increasing morass of corresponding equations; with them, the puzzling infinities could be tamed systematically in a process called "renormalization." Like most of his colleagues and former teachers, Feynman approached the problem *perturbatively*: solutions for complicated interactions could be approximated by adding higher- and higher-order corrections to solutions of less complicated situations. The diagrams served as a means of keeping track of these higher-order correction terms. The pictures, in other words, were a form of bookkeeping.[12]

Freeman Dyson, at the time a graduate student at Cornell in close contact with Feynman, quickly codified the so-called Feynman rules, which dictated how specific features of the diagrams corresponded one-to-one with particular mathematical expressions: a straight line in a diagram meant that a certain factor had to be in-

TABLE 8–2

The correspondence between diagrams and S-matrix elements in momentum space

Component of Diagram	Factor in S-Matrix Element	
Internal photon line	$g_{\nu\lambda}\dfrac{1}{k^2 - i\mu}$	photon propagation function
Internal electron line	$\dfrac{i\not{p} - m}{p^2 + m^2 - i\mu}$	electron propagation function
Corner	$\gamma^{\nu}\delta(p - p' - k)$	
External photon lines	$\dfrac{1}{\sqrt{2\omega}}\, e_{\mu}(\mathbf{k}),\ \dfrac{1}{\sqrt{2\omega}}\, e_{\mu}(\mathbf{k})$	ingoing and outgoing photons
External negaton lines	$\sqrt{\dfrac{m}{\epsilon}}\, u(\mathbf{p}),\ \sqrt{\dfrac{m}{\epsilon}}\, \bar{u}(\mathbf{p})$	ingoing and outgoing negatons
External positon lines	$\sqrt{\dfrac{m}{\epsilon}}\, \bar{v}(\mathbf{p}),\ \sqrt{\dfrac{m}{\epsilon}}\, v(\mathbf{p})$	ingoing and outgoing positons

FIGURE 1. The "Feynman rules" in the momentum-space representation. Note that the "S-Matrix Elements" referred to here are for quantum electrodynamics, not for the autonomous S-Matrix theory. From J. M. Jauch and F. Rohrlich, *The Theory of Photons and Electrons* (Cambridge, Mass., 1955), 154. Reproduced by kind permission of Perseus Books Publishers, a member of Perseus Books, L.L.C.

cluded in the accompanying equation; a wavy line indicated a different mathematical factor. The number of "corners" or "vertices" at which different lines came together in the diagram dictated how many factors of the "coupling constant" had to be multiplied in that particular equation, and so on.[13] Josef Jauch and Fritz Rohrlich made these one-to-one equivalences especially apparent in a table within their 1955 textbook, reproduced in figure 1: each piece of the diagrams bore a unique mathematical meaning. Thus electrons could simply propagate without scattering, as pictured in the Feynman diagrams in figure 2, from the prominent textbook *Mesons and Fields* (1955) by Silvan Schweber, Hans Bethe, and Frederic de Hoffmann (fig. 2). Or electrons could scatter by exchanging a single "virtual photon,"

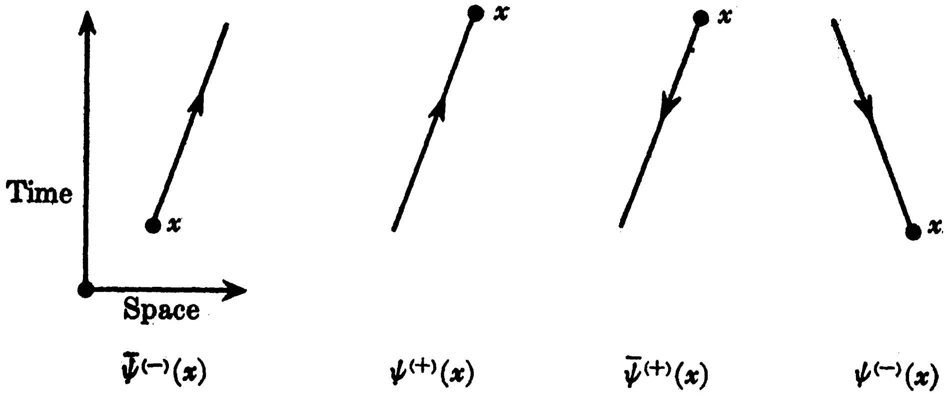


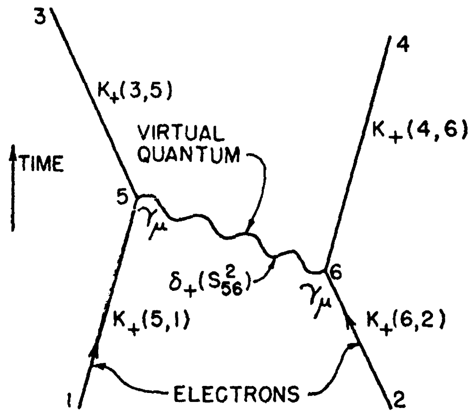
FIGURE 2. Feynman diagrams for electrons and positrons propagating without scattering. From S. Schweber, H. Bethe, and F. de Hoffmann, *Mesons and Fields* (White Plains, N.Y., 1955), 1:219.

as Feynman indicated with his first published Feynman diagram, reproduced here in figure 3.[14] In either case, theorists and students alike could simply use the table in figure 1 to translate their diagrams directly into mathematical form.

Electrons could scatter in still more complicated ways, however, and physicists knew that they had to include these other possible means of scattering in their total calculation. Feynman diagrams could be used to keep track of these more complicated correction terms in a systematic way, as Feynman indicated with the examples reproduced in figure 4. As one example, consider the diagram marked *c*: one of the electrons could emit a virtual photon, which could itself disintegrate en route into an electron-positron pair; these could then annihilate to form a new photon, which would then continue on its way and smack into the second electron.[15] Still further correction terms could be calculated by adding more and more vertices in the diagrams and using the table in figure 1 to translate these complicated diagrams into specific mathematical expressions. In each case, theorists following Feynman's and Dyson's lead learned to associate specific features of the diagrams directly and uniquely with pieces of their mathematical equations. Using the diagrams, physicists could snap components of their quantum-field-theory calculations into place.

Streamlining in this way what had previously been laborious calculations, Feynman's pictorial tool gained adherents swiftly, principally through early articles and lectures by Dyson. In fact, within six months of Feynman's original blackboard demonstration, the diagrams began to appear in articles in the *Physical Review*, and they quickly became commonplace for studies within quantum field theory. A series of new textbooks featured the diagrammatic techniques, always emphasizing, as Jauch and Rohrlich did with their table in figure 1, the strict one-to-one correspondence between each feature of the diagrams and each mathematical factor in the

FIGURE 3. The simplest Feynman diagram for electron-electron scattering. From R. P. Feynman, "Space-Time Approach to Quantum Electrodynamics," *Physical Review* 76 (1949): 772. © 1949 American Physical Society; reproduced by kind permission.



accompanying equations. A cartoon from *Physics Today*, printed years after the diagrams' introduction, caricatured field theorists' reliance upon the diagrams (see fig. 5). As Richard Mattuck explained when he reprinted the cartoon in his 1967 textbook, it was "possible in principle" to attempt "perturbation theory without diagrams, just as it is possible to go through the jungles of the Amazon without a map. However, the probability of survival is much greater if we use them."[16] The diagrams' pictorial elements and mathematical meaning were codified in a series of textbooks throughout the 1950s and 1960s. Drawing on these textbooks, students of quantum field theory learned to begin their studies diagrammatically.

Yet this victory for renormalizable quantum electrodynamics, in terms of Feynman diagrams and their associated rules for translating between diagrams and the mathematics of field theory, was short-lived. Beginning soon after World War II, huge particle accelerators began to probe energies higher than had ever been achieved before.[17] As the energies of particle scatterings rose, physicists soon found a zoo of unexpected particles and interactions, well beyond the simple case of electrons, positrons, and photons treated by quantum electrodynamics.[18] Theorists hit trouble immediately with the so-called strong interactions, which seemed to bind certain nuclear particles together. For example, the strong interaction kept protons and neutrons bound together within atomic nuclei. Although field-theoretic interaction terms could be postulated in analogy with the quantum electrodynamics case, the Feynman-Dyson diagrammatic techniques no longer seemed at all effective: unlike the case of the relatively weak electromagnetic force treated by quantum electrodynamics, theorists could find no consistent scheme for separating the main contribution to a strong-force calculation from what should have been smaller, higher-order correction terms.[19] Perturbation theory had broken down.

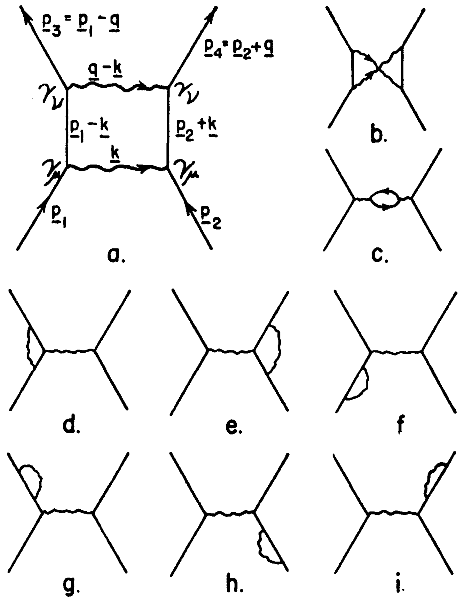


FIGURE 4. Feynman diagrams for electron-electron scattering correction terms; these diagrams play the role of "bookkeepers" for the perturbative analysis. From Feynman, "Space-Time Approach to Quantum Electrodynamics," 787. © 1949 American Physical Society; reproduced by kind permission.

With the failure of perturbation theory, one might have expected Feynman diagrams to lose their usefulness or appeal to particle physicists—after all, the diagrams seemed to derive their usefulness *precisely* and exclusively from their use in perturbative bookkeeping. Yet rather than toss away Feynman diagrams in the face of these frustrations, many theorists began to exploit the diagrams in newfound, unprecedented ways. Some physicists put Feynman diagrams to work in the service of a series of new calculational schemes *different* from the Feynman-Dyson arrangement. Where field theorists had exploited the unique, one-to-one associations between Feynman diagrams and particular mathematical expressions, other particle theorists effectively pried the two halves of figure 1 apart, holding fast to the picturesque doodles while discarding the original mathematical rules for their use.[20] By the mid-1950s, many theorists had decided that Feynman diagrams did not have to mean what they had meant in 1949, nor did they have to be used in the same way.

Perhaps the largest break between Feynman diagrams and quantum field theory came with Geoffrey Chew's *S*-matrix program. Dyson's rendition of the Feynman rules for quantum field theory had relied upon three key ingredients: (*a*) interactions occurred due to the exchange of virtual particles; (*b*) the form of the interactions was governed by a mathematical Hamiltonian function, which described the energy associated with the basic, unit interaction; and (*c*) interactions could be studied perturbatively. Chew rejected each of these in turn. Announcing his break with great gusto at the June 1961 La Jolla meeting, Chew argued that quantum fields and virtual particles simply did not exist (or at least supposing that they did seemed to offer no good way to understand the strong interactions). Hamiltonians and their associated mathematical techniques were useless for studying the strong interactions. And, because of the strong interactions' strength, perturbation theory was hopeless. Every aspect of field theory that had originally governed Feynman diagrams' meaning and use now struck Chew as "sterile." And yet despite having their very basis and definition discarded, Chew clasped Feynman diagrams as a surefire way to proceed.[21]

In Chew's hands, not only were the original Feynman rules discarded for the diagrams' use; Chew and his fast-growing band of students and collaborators began to fill in *new* meanings and uses of the diagrams, which had no correlate with anything field-theoretical. In some cases, physicists actually employed the diagrams in a leading, generative role for fashioning new concepts. In each of these developments, Chew put his reliance upon Feynman diagrams up front, severed as they were from their field-theory umbilical. He emphasized in his 1961 lecture notes that many of the new results of his developing theory were "couched in the language of Feynman diagrams," even though, contrary to first appearances, they did not "rest heavily on field theory." "It appears to me," he further prophesied, "likely that the essence of the diagrammatic approach will eventually be divorced from field theory" altogether.[22] Reinterpreting the diagrams, Chew all the while denounced the very theory from which the diagrams had come.

Where Feynman had begun doodling his stick figures to keep track of higher- and higher-order corrections in a perturbative expansion of quantum electrodynamics, marking carefully the inclusion of more and more virtual particle exchanges and their effects on the electron's elementary quantum field, Chew and his many students gleefully exploited the diagrams in their campaign to overturn quantum field theory. On their blackboards, scratch pads, research articles, and

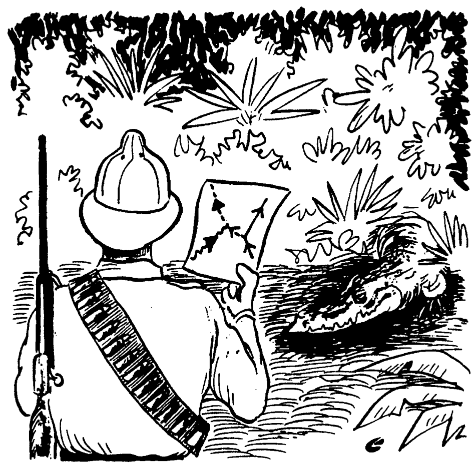


FIGURE 5. "Feynman diagrams in the Amazon jungle." From R. D. Mattuck, *A Guide to Feynman Diagrams in the Many-Body Problem* (New York, 1976 [1967]), 120. Reproduced by kind permission of the McGraw-Hill Companies.

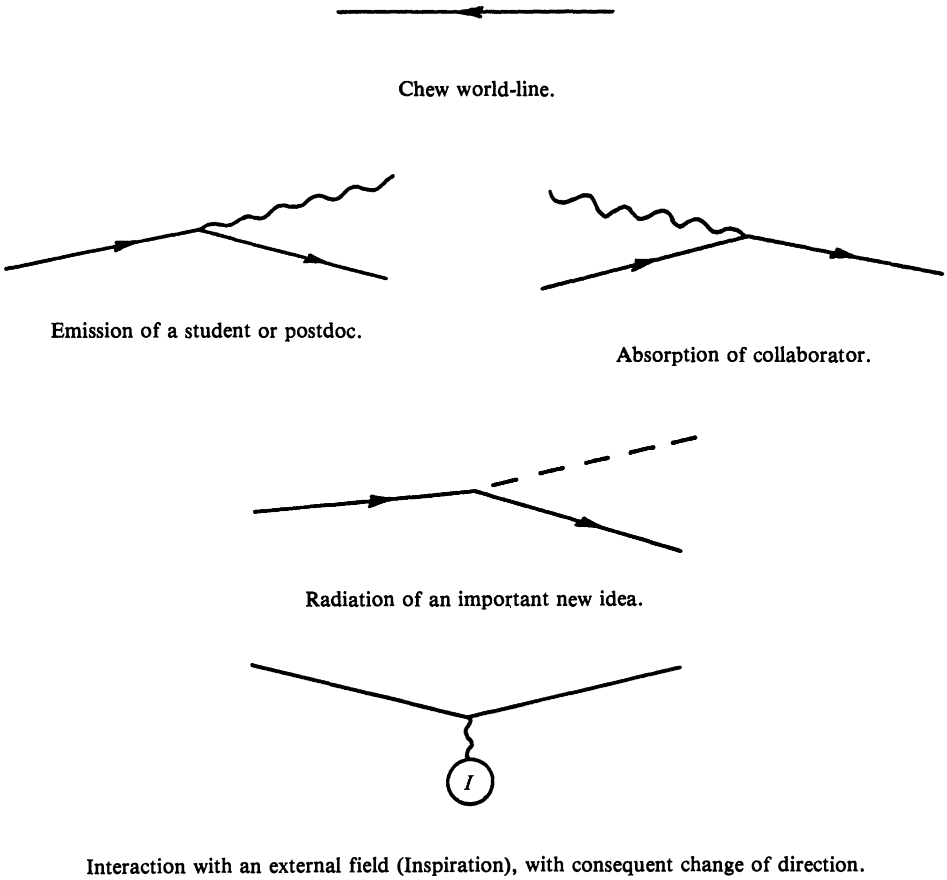
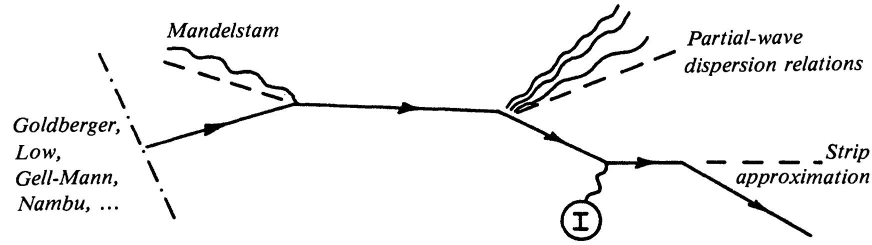


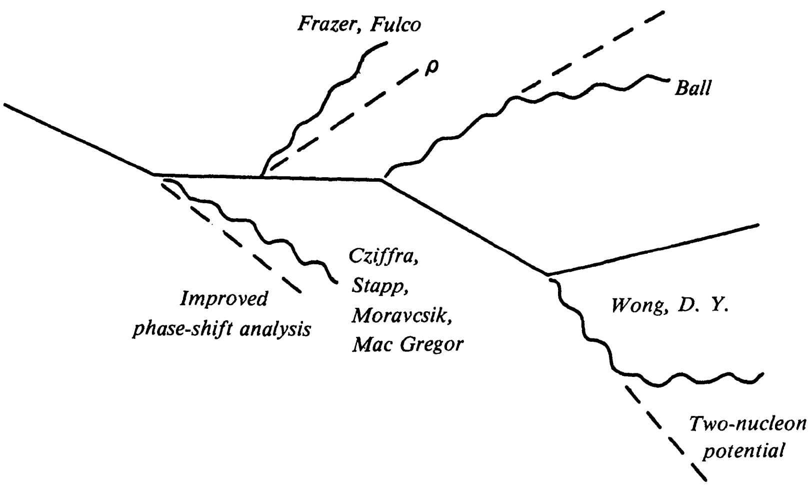
FIGURE 6. William Frazer's revised "Feynman rules." From W. R. Frazer, "The Analytic and Unitary *S* Matrix," in *A Passion for Physics: Essays in Honor of Geoffrey Chew*, ed. C. DeTar et al. (Singapore, 1985), 1–3. Reproduced by kind permission of Dr. William Frazer and the World Scientific Publishing Company.

textbooks, the diagrams carried none of these older, specific field-theory meanings. Gone were all ties to Hamiltonians and the virtual particles of quantum field theory. Gone too was all talk of perturbation expansions, and hence of the diagrams' role in keeping track of higher-order correction terms. Instead, the same unadorned lines of Feynman's stick figures offered Chew and company a window onto an effervescent microworld of strongly interacting particles and processes. Though drawn nearly the same way pictorially by Feynman in 1948 and by Chew in 1964, the meaning imputed to the diagrams could not have been more different.

William Frazer, who completed his Ph.D. under Chew's direction in 1959, re-



The 1958–61 period: development of partial-wave dispersion relations.



The 1959–60 shower of students, ideas.

FIGURE 7. Frazer's version of Chew's career. From Frazer, "Analytic and Unitary *S* Matrix," 3–4. Reproduced by kind permission of Dr. William Frazer and the World Scientific Publishing Company.

cently retold the story of Chew's distinguished career. As a fitting tribute, Frazer once again turned to Feynman diagrams. Redefining yet one more time what the diagrams' lines "meant," Frazer laid out Chew's long series of interactions with students, collaborators, and inspiring new ideas (see figs. 6–7).[23] As Frazer's toast to his former advisor makes clear, theorists of all stripes could cling to Feynman diagrams as their own special totems.

Throughout the prolonged contests between quantum field theorists and *S*-matrix theorists in the 1960s, Feynman diagrams proved to have a tremendous resiliency. On each side, students of particle physics began their studies diagrammatically; from the large body of theorists' practices, the diagrams thrived while other calculational procedures withered. And thus the question: whence the diagrams' staying power? The following three sections develop some explanations by placing the ubiquitous diagrams within larger visual traditions.

Conventions and the Pedagogical Assimilation into a Visual Tradition

At first glance, the widespread use and persistence of Feynman diagrams, at least within quantum field theory, might be attributed to the extreme ease and convenience of calculating with the diagrams; after all, many physicists recounted watching with awe as Feynman himself calculated complicated quantities in mere minutes at a blackboard.[24] The unparalleled ease and streamlining brought by the diagrams' use within quantum field theory cannot be denied. Years after the diagrams' introduction, Feynman's rival Julian Schwinger even sneered that Feynman diagrams had brought "computation to the masses."[25] But ease alone cannot be the whole story, for "convenience" cannot explain the *leading* role assigned by many theorists to the diagrams, as they redefined the diagrams' meanings and uses and made their break from quantum field theory.

Part of the explanation of the diagrams' resilience will be pursued in this section. Taking seriously remarks by art theorists Goodman and Gombrich, we may pay close attention to the specific ways in which the Feynman diagrams were drawn and taught. By focusing on the pictorial *conventions* according to which the diagrams were drawn, the diagrams' assimilation into a preexisting visual tradition becomes clearer.[26] These larger, pre-field-theoretic associations may have given the diagrams a certain primacy and autonomy for theorists of both the field-theory and *S*-matrix camps.

Feynman diagrams began to circulate beyond the Pocono Manor in a pair of articles published in 1949 by Freeman Dyson. Dyson's explicitly pedagogical treatment of the diagrams illustrates their conventional nature. In the same imperative voice that would guide so many American hobbyists during the 1950s to "paint by numbers," Dyson laid out Feynman's graphical means of calculating in quantum electrodynamics. He began, "The points $x_0, x_1, \ldots x_n$ may be represented by $(n + 1)$ points drawn on a piece of paper."[27] No mere thought experiment, these diagrams were actually to be drawn on a real piece of paper! With these points laid out, the lesson continued. Dyson's instructions are worth examining here, not for the specific technical elements listed, but rather as an illustration that the diagrams did not claim universal familiarity at first sight; Dyson had to spell out, step by step, just exactly how the diagrams themselves should be drawn and interpreted:

For each associated pair of factors $(\underline{\psi}(x_i), \psi(x_{ri}))$ with $i \neq k$, draw a line with a direction marked in it from the point x_i to the point x_{ri}. For the single factors $\underline{\psi}(x_k)$, $\psi(x_{rk})$, draw directed lines leading out from x_k to the edge of the diagram, and in from the edge of the diagram to x_{rk}. For each pair of factors $(A(x_{si}), A(x_{ti}))$, draw an undirected line joining the points x_{si} and x_{ti}. The complete set of points and lines will be called the "graph" of M [the mathematical quantity associated with this Feynman diagram]; clearly there is a one-to-one correspondence between types of [mathematical] elements [M] and graphs. . . . The directed lines in a graph will be called "electron lines," the undirected lines "photon lines."[28]

Dyson had to instruct his readers explicitly that certain lines in the diagrams would be dubbed "electron lines" and others "photon lines"; this interpretation of the lines was not in itself an obvious consequence of laying out random points on a piece of paper and drawing bare lines between them. Dyson's methodical presentation highlights the diagrams' artificiality: like a child's game of connect-the-dots, the diagrams, in Dyson's hands, provided a conventional representational scheme with no pretensions to picturing actual particles' real scatterings.

When introducing the so-called Feynman rules, which dictated the diagrams' use within quantum field theory, every textbook from the 1950s and 1960s followed Dyson's lead. From these textbooks, it further becomes clear that Feynman's diagrams and their field-theoretic use were neither automatic nor necessarily obvious; like Dyson's very explicit instructions, the diagrams' use and specific pictorial conventions had to be built up step by step. Consider the treatment by Schweber in volume 1 of *Mesons and Fields* (1955). Talk of "conventions" abounds: the "direction of increasing time is supposed to be upward," in the Feynman diagrams, which dictated how the "arrow convention" on the directed electron and positron lines would be established; the action of an external potential at a given point is "sometimes exhibited explicitly by representing the external potential by a wavy line with a cross at the end"; the contraction of two boson factors in a meson theory would be "represent[ed] . . . by a dashed line joining x_1 and x_2," and so on.[29] Franz Mandl similarly introduced the diagrams in his 1959 text amidst repeated talk of the "conventions"—his word—according to which they should be drawn.[30] Kenneth Ford labeled one of these conventions an "artistic trick" in his book from 1963.[31] A later text explained, "We shall agree to represent a free operator $A_\mu(x)$ by an (undirected) dotted line leading from the vertex x beyond the boundaries of the diagram," with similar conventions "agreed upon" for the other operators.[32] Every aspect of the diagrams, from which points to be connected to the types of lines, directions of arrows, and positions of crosses, had to be built up for the students. Like seventeenth-century artists learning to draw landscapes and human faces from copybooks filled with specific visual schemata, students of these physics textbooks followed step-by-step instructions for how to draw Feynman diagrams.[33]

The lessons were not always quickly learned. Though a prominent Berkeley theorist reported that the diagrams were "widely used" as early as 1950, their artificiality or conventionality still stymied some students into the 1950s. In recommending his Ph.D. student for a position in Berkeley's physics department in 1953,

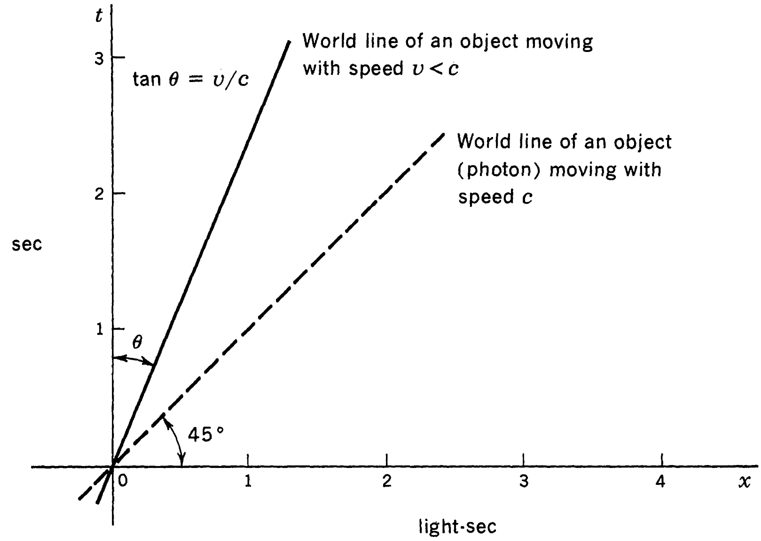


FIGURE 8. Minkowski diagram. From N. David Mermin, *Space and Time in Special Relativity* (New York, 1968), 160. Reproduced by kind permission of the McGraw-Hill Companies.

for example, Leonard Schiff made a point of mentioning that the recent student "understands the Feynman-Dyson techniques, and has used them in his thesis calculations."[34] The need to spell this out so clearly in a recommendation letter speaks to the larger point that graduate students' ability to use Feynman's diagrammatic method could not always be taken for granted in the early 1950s. (Such a statement would have been unthinkable by the late 1950s, by which time familiarity with Feynman's diagrammatic technique was simply assumed for all recent Ph.D.s in theoretical particle physics.) Feynman diagrams were not an automatic representational scheme. They were "conventions" that had to be taught and practiced, sometimes more explicitly than others.

Although the diagrams may have been merely "conventional," these conventions were not chosen at random. Instead, the visual features and elements followed almost trivially from an earlier visual-representational tool, which had been completely standardized long before the 1950s, and which was taught to students from their first courses in college physics: Minkowski diagrams of special relativity. Hermann Minkowski had introduced space-time diagrams for the study of special relativity in 1909. Drawing a time axis vertically and a single spatial axis horizontally, objects' "worldlines," or paths through space and time, could be charted.[35] An object at rest in a given frame of reference, then, would trace out a worldline moving vertically straight up the page: its spatial position would not change as time went by. An object traveling with a constant speed in a particular direction, on the other hand, would trace out a worldline inclined away from the vertical at some angle. With the aid of these Minkowski diagrams, or "space-time diagrams" as they were often called, students began their study of special relativity at an early age.

According to custom, students learned to scale the speed of light to one, so that light rays would travel along 45° diagonals in Minkowski diagrams. Furthermore, because Albert Einstein's special relativity elevated the speed of light to an absolute speed limit obeyed by all other objects, any other object's worldlines would necessarily have a slope greater than 45°; that is, all objects, from airplanes to automobiles to atoms, would dance around at speeds less than the speed of light. A worldline that extended straight horizontally would picture the unphysical situation of an object traveling with infinite speed, taking no time to traverse greater and greater spatial distances. Comparison of the Minkowski diagram in figure 8 with the Feynman diagrams reproduced in figures 2 and 3 begins to reveal the diagrams' similarity.

This tacit, visual assimilability between Feynman's doodles and Minkowski diagrams had stirred Niels Bohr, that elder statesman of quantum physics, to vigorous objections during Feynman's presentation at the 1948 Pocono meeting. Chalk in hand, Feynman had been interrupted by Bohr's challenge: Werner Heisenberg's uncertainty principle, lying at the very heart of quantum mechanics, forbade discussion of particles' trajectories in space and time; yet this seemed to be precisely what Feynman was doodling on the blackboard. According to quantum mechanics, an elephant's worldline may be plotted with aplomb on a Minkowski diagram, but not an electron's: doing so would imply simultaneous knowledge of the quantum particle's position and momentum. Feynman's flustered reply, that his diagrams were not meant to be read as literal space-time trajectories but rather as a shorthand notation, convinced few in the room.[36]

In this first episode, we see signs of a tension that would follow Feynman's diagrams over the next two decades. *Yes*, they were "merely conventions," and *yes*, they carried for many physicists a very strong, if at times tacit, association with the Minkowski diagrams that Bohr at first took them to be. Here we see Goodman's and Gombrich's notions of the role of habit-formation and inculcation come to play. The specific representational schemata of the Feynman diagrams were often precisely equivalent to those of the Minkowski diagrams. This slippage, at times exploited by physicists and at other times ignored or denied, provides one clue as to how Feynman diagrams came to command such ready usage in the months and years following their introduction. By incorporating several specific pictorial conventions from the Minkowski diagrams, already "second nature" for physicists by the 1950s, Feynman's diagrams could quickly be assimilated within a larger, and quite familiar, visual tradition.

The specific similarities may be considered still further. Dyson's and Feynman's original 1949 articles introducing the diagrams all began with Feynman diagrams drawn in space and time; Feynman's famous articles further began with explicit talk of electrons' and positrons' "worldlines" and returned often to the question of the appropriate ordering of "events" along these particles' "trajectories."[37] Schweber's 1955 textbook treatment similarly introduced Feynman diagrams with talk of electrons' "worldlines."[38] Josef Jauch and Fritz Rohrlich noted in their own 1955 textbook that the lines within Feynman diagrams "suggest the obvious meaning of world lines for particles entering and leaving the reaction."[39] Though this specific language was not always echoed in the later textbooks, the visual scheme was: *every single textbook treatment* of Feynman diagrams published during the 1950s and 1960s first introduced Feynman diagrams in space and time, usually with the "time" axis labeled explicitly. Like the Minkowski diagrams, the time axis ran vertically and the spatial axis ran horizontally.[40]

This complete uniformity of beginning with space-time Feynman diagrams is particularly surprising because no actual calculations were completed in the x and t coordinates. Invariably, as Dyson and Feynman themselves had done, each textbook introduced the diagrams in space and time first, establishing the line-type and arrow conventions as noted above, and only later (often several sections or even a whole chapter later) switched to the momentum-space representation of the Feynman diagrams for beginning real calculations.[41] Years before even the earliest texts had been written, it had indeed become common for published diagrammatic calculations to proceed directly in momentum space.[42] By continuing to introduce the diagrams in space and time, these textbook authors borrowed on the long pedagogical tradition of charting particles' propagation with Minkowski-styled space-time diagrams.

Moreover, the first Feynman diagrams to appear in many of these articles and books made use of a further specific Minkowski diagram scheme: scaling the speed of light to one so that lightlines lay along 45° diagonals, with all massive particles lying along worldlines with steeper slopes (and thus moving with lesser speeds, according to the Minkowski diagram conventions). Again, Feynman's own first published diagrams followed this trend (see fig. 3); in fact, even after he had shifted calculations to momentum space, several diagrams followed these Minkowski diagram conventions.[43] When building up the diagrammatic machinery in their textbooks, Schweber, Mandl, Robert Leighton, Paul Roman, James Bjorken and Sidney Drell, and Feynman himself similarly followed these specific visual cues for their *first* Feynman diagram examples.[44] Although later examples within these articles and textbooks usually did not follow this particular convention, and showed exchanged particles propagating straight-horizontally (which, according to the Minkowski diagram conventions, would imply unphysical, instantaneous propagation), the very first diagrams followed closely Minkowski's conventions for picturing particles' propagation through space and time.[45] The persistence of these Minkowski-like tilted lines within the early Feynman diagrams points immediately to "added structure" beyond Dyson's bare-bones instructions, which had merely been to lay out a series of points $x_0 \ldots x_n$ on a piece of paper and connect the dots.

As a teaching device, these first Feynman diagrams, drawn carefully to Minkowski's specifications, borrowed on the "intuitive appeal" of a familiar tradition.

Nor did these associations always remain tacit. Jauch and Rohrlich, for example, explained in a footnote within their *Theory of Photons and Electrons* (1955),

> In this and the following figures the [Feynman] diagrams are stylized. Although an interpretation in terms of world lines is sometimes given, this fact is irrelevant here and will be ignored. Consequently, external photon lines are not always drawn at 45° to the time axis (which is upward), and external electron lines are drawn parallel to the time axis even when these electrons are not meant to be at rest. Similarly, internal photon lines are often drawn perpendicular to the time axis, even though instantaneous interaction is not necessarily implied.[46]

With the prior conventions for depicting particles' propagation so firmly established, Jauch and Rohrlich feared that the "stylized" look of their Feynman diagrams could be deceiving. A similar footnote from Ernest Henley and Walter Thirring's *Elementary Quantum Field Theory* (1962) cautioned readers: "These diagrams should not be taken too literally, since the concept of a classical path does not apply to virtual particles."[47]

Still, these cautions and caveats aside, several other physicists actively encouraged the associations between Minkowski and Feynman diagrams. Richard Mattuck talked openly about the connection between Minkowski and Feynman diagrams in his well-known 1967 textbook. Physicists also exploited these similarities when lecturing to undergraduate classes and audiences of nonphysicists. "Popular" books by Kenneth Ford, Stanley Livingston, and even by Feynman himself proceeded seamlessly from an introduction of Minkowski diagrams to space-time Feynman diagrams (see fig. 9).[48] These popular books, of course, were hardly finding much place in graduate students' curricula. They illustrate, however, that the assimilability of Feynman to Minkowski diagrams was itself not a difficult or wholly foreign notion to particle physicists at the time.

Thus, despite Feynman's own verbal denials to Niels Bohr that his diagrams were intended literally to picture particles' physical paths, they were consistently drawn *and taught* as being of a piece with the reigning pictorial standards for studying particle trajectories through space and time. The mnemonic device simply was not "innocent" of physicists' prior inculcation in the visual practice of depicting particle paths, regardless of the distinct meaning attributed in different contexts to the stick figures. If we were to follow Nelson Goodman, then, perhaps our story would be complete: the resilience displayed by Feynman's diagrams in the early 1960s, when some physicists such as Geoffrey Chew aimed to build a new theory from Feynman diagrams while replacing quantum field theory altogether, can be explained by the fact that the diagrams were trivially assimilable into a long visual tradition for treating particles' propagation. This long tradition carried tacit, visual "baggage" far more general than the specific functions Feynman diagrams had been designed to play in field theory. Habit and inculcation, in other words, may

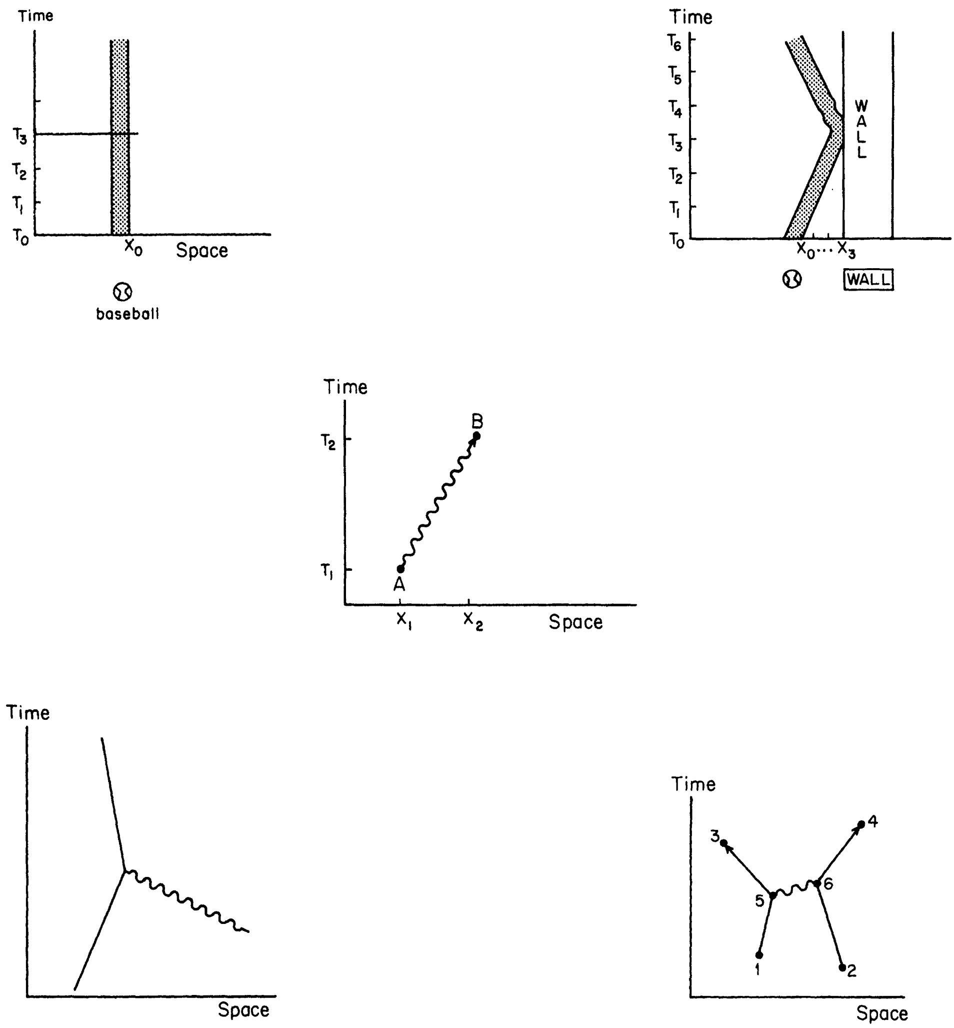


FIGURE 9. Minkowski and Feynman diagrams. From R. P. Feynman, *QED: The Strange Theory of Light and Matter* (Princeton, 1985), 86–88, 92, 94. © 1985 Princeton University Press; reproduced with kind permission.

have been enough to secure Feynman diagrams a central place in particle physicists' heads and hands, even if their connections with other elements of a given theory came and went.

With Gombrich, Snyder, and Mitchell, however, we may be skeptical that "habit" alone is sufficient to explain the diagrams' tenacity. In just this period of upheaval among theories of the strong interaction, a second diagrammatic tool was developed, quite distinct from Feynman diagrams. Although these other diagrams offered equally strong ties to pedagogical inculcation and habit, they suffered quite a different fate. The comparison between Feynman diagrams and these "dual diagrams" can begin to highlight which features specific to the Feynman diagrams contributed to their staying-power.

Not Just Any Habit: The Case of Dual Diagrams

Soon after Chew and others called for a wholesale replacement of quantum field theory, a team from England developed a pictorial device to complement Feynman diagrams in the study of particles' interactions. John Polkinghorne, in particular, then saw to it that the "dual diagrams" became well known. Polkinghorne focused his summer school lectures from 1960 on the new diagrams; several articles were dedicated to the diagrams and their use; and they featured prominently in the textbook from 1966 by Polkinghorne and his colleagues, *The Analytic S-Matrix*.[49]

The dual diagrams offered what Polkinghorne repeatedly called a "picturesque geometrical construction" for finding and characterizing certain physical properties of generic interactions. In the *S*-matrix work, as championed by Geoffrey Chew and his colleagues, the overriding concern was charting the regions in which the mathematical functions describing particles' scattering behaved as proper analytic functions. Feynman diagrams, as interpreted according to the Soviet physicist Lev Landau's new rules for them, provided one means of trying to find and characterize these analytic properties but, as Polkinghorne and collaborators soon discovered, could not be relied upon to catch all the subtle features alone.[50] Instead, a dual diagram could be introduced for any given Feynman diagram: for every vertex in the Feynman diagram there would appear a closed loop in the dual, and vice versa (see fig. 10). With the aid of the dual diagrams, Polkinghorne demonstrated, one could analyze in a geometrical fashion which particles carried how much momentum in a given interaction and, hence, which specific processes would dominate in particles' scattering. The dual diagrams could thus be used to isolate mathematical anomalies that had been missed in the first attempts to rely solely on Feynman diagrams and could thereby steer the *S*-matrix theorists toward a more complete survey of the mathematical structure associated with a given process.[51]

As Landau demonstrated, and as noted explicitly in the pedagogical writings of Polkinghorne, the rules for building the dual diagrams were exactly analogous to Kirchhoff's rules for electric circuits.[52] This structural equivalence is significant: students learned how to study the current flowing through elementary circuits, using simple circuit diagrams and Gustav Kirchhoff's rules, even before they learned

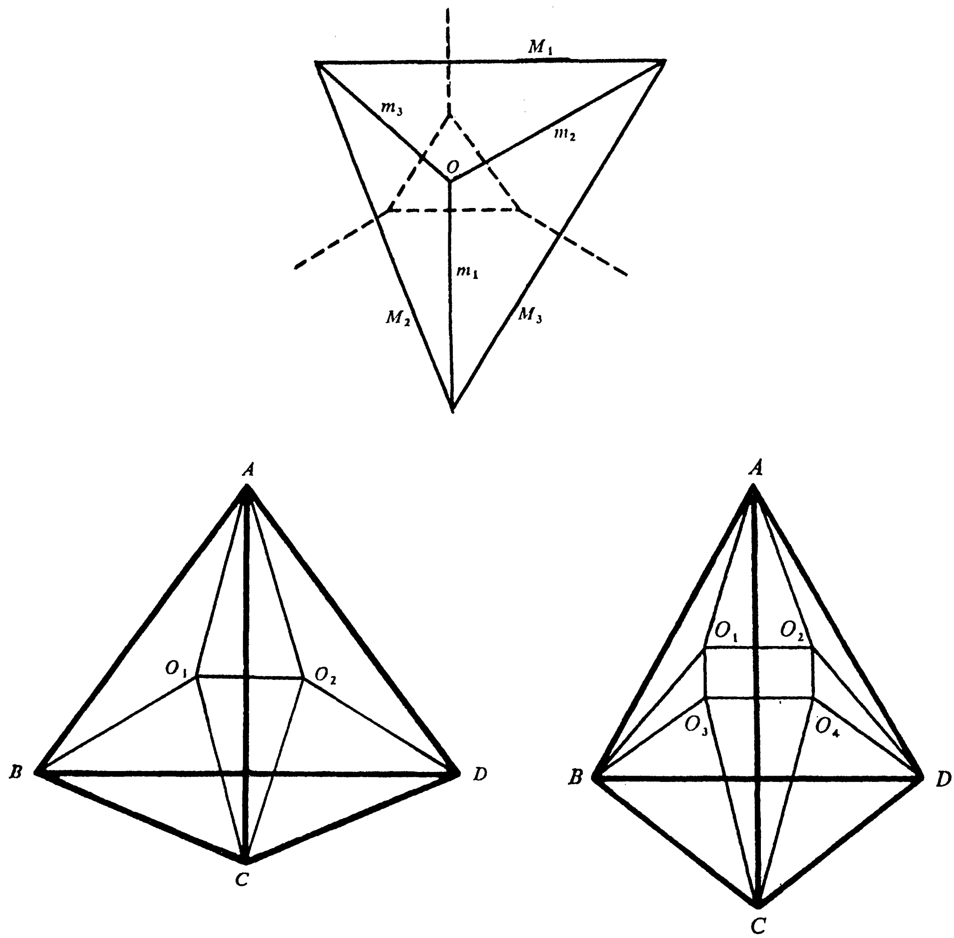


FIGURE 10. Dual diagrams. The top figure shows the dual diagram (solid lines) associated with the superimposed Feynman diagram (dashed lines). The bottom two figures show examples of more complicated dual diagrams. From J. C. Polkinghorne, "The Analytic Properties of Perturbation Theory," in *Dispersion Relations*, ed. G. R. Screaton (New York, 1961), 67, 80. Reproduced by kind permission of the Reverend Dr. John Polkinghorne.

about Minkowski space-time diagrams and special relativity—and long before they began to tackle particle physics. What Polkinghorne emphasized out loud and at length was the long-standing pedagogical tradition from which dual diagrams derived: in studying the flow of momentum around a given vertex, students only had to apply the same rules and skills that they had learned in their earliest studies in physics. Where the connection between Feynman diagrams and Minkowski diagrams was often a hushed one within textbooks on quantum field theory, here Polkinghorne and others worked hard to make the visual and calculational associations between dual diagrams and circuit diagrams clear.

Yet despite the attention dedicated to the dual diagrams, these alternative diagrams never entered physicists' "toolkit" the way Feynman diagrams did. Geoffrey Chew, for example, leading spokesman for the *S*-matrix program, himself never once used dual diagrams in his research articles, lecture notes, or textbooks. These diagrams are historically significant, then, for at least two reasons. First, they did not *look* like Feynman diagrams; it was not predetermined in 1959 that the *S*-matrix theorists, just at the time they were seeking to overthrow quantum field theory, should continue to rely so exclusively on Feynman diagrams. A contrasting diagrammatic technique was put forward, shown to be more effective than Feynman diagrams alone for certain crucial tasks, and yet still was not exploited. Second, the untimely death of the dual diagrams illustrates just the point that Gombrich, Snyder, and Mitchell sought to append to Goodman's discussion: invoking habit, training, and inculcation alone is insufficient to discriminate between competing kinds of visual depictions, or of explaining why only certain visual tools get accorded special status. Dual diagrams should have been just as easy to teach to young particle theorists in 1960 as Feynman diagrams: where one drew on Kirchhoff's laws, the other drew on Minkowski diagrams. Yet the non-space-time dual diagrams, although easy to "acquire," did not interest most theorists.

With Gombrich, Snyder, and Mitchell, then, we may return to the case of Feynman diagrams and ask what was *particular* about these "paper tools" for the community of high energy particle theorists at midcentury that might have further contributed to these diagrams' staying power.[53]

From Mnemonic to Mimetic: Reifying Feynman Diagrams

Historians of science have produced many examples over the past few years of visual representational schemes that were introduced as mnemonic devices, but that gained, often for the next generation of practitioners, an added sense of realism. Whether describing stratigraphical columns in eighteenth-century geology, Michael Faraday's force lines in early nineteenth-century electromagnetism, chemical formulas in 1840s organic chemistry, indicator diagrams from 1860s steam engines, pictures of antibodies in turn-of-the-century immunology, or models of the earth's crust in 1920s isostasy, representations that had been developed as convenient ways to talk about the world came to be treated by others as pictures of how the world really was.[54]

Some physicists, too, saw in the Feynman diagrams more than just a convenient mnemonic device. In his first article on the diagrams, Freeman Dyson noted Feynman's own attitude toward the diagrams—not an attitude that Dyson himself shared. Dyson wrote that to Feynman, a particular Feynman diagram was "regarded, not merely as an aid to calculation, but as a *picture* of the physical process" under study.[55] By the mid-1960s, similar statements could be found in several textbooks. Stephen Gasiorowicz, for example, proclaimed that the Feynman diagrams "not only serve as a simple device that keeps track of all the terms to be calculated, but also have associated with them a definite physical picture of the process. Such pictorial representations are sometimes useful in stimulating guesses of possible important contributions in a certain energy range."[56]

The next year, Richard Mattuck pressed this point even more strongly in his own textbook, published in 1967. He included a special section to address explicitly the question of how to interpret Feynman diagrams. Under the boldface subheading, "The 'quasi-physical' nature of Feynman diagrams," Mattuck explained that "because of the unphysical properties of Feynman diagrams [that is, their depiction of "virtual" processes that do not conserve energy], many writers do not give them any physical interpretation at all, but simply regard them as a mnemonic device for writing down any term in the perturbation expansion." This kind of nominalism was not sufficient for Mattuck, as he continued,

> However, the diagrams are so vividly "physical-looking," that it seems a bit extreme to completely reject any sort of physical interpretation whatsoever. As Kaempffer points out, one has to go back in the history of physics to Faraday's "lines of force" if one wants to find a mnemonic device which matches Feynman's graphs in intuitive appeal. Therefore, we will here adopt a compromise attitude, i.e., we will "talk about" the diagrams as if they were physical, but remember that in reality they are only "apparently physical" or "*quasi-physical.*"[57]

It is interesting to contrast Mattuck's obvious glee for the diagrams' "vivid, 'physical-looking'" characteristics with F. A. Kaempffer's original discussion, on which Mattuck has drawn here in quite an incomplete fashion. Where Mattuck summarized Kaempffer's description of Feynman diagrams' "intuitive appeal," Kaempffer himself had labeled their attraction a "propagandistic persuasiveness." In fact, Kaempffer had outlined the historical analogy to Faraday's work to serve explicitly as a "timely warning against all too literal acceptance of mental images based mainly on a fabric of *conventions*, however consistent that fabric may appear." Much as James Clerk Maxwell was led to a literal acceptance of an ether by the pictorial representation of Faraday's force lines, Kaempffer warned that "similar temptations are lurking behind Feynman's graphs."[58] Whereas Kaempffer read such "temptations" as potentially misleading for the physicist, Mattuck delighted in the conventionalized diagrams, which looked so real they simply couldn't be of merely mnemonic value. A more recent textbook makes this realism claim visually,

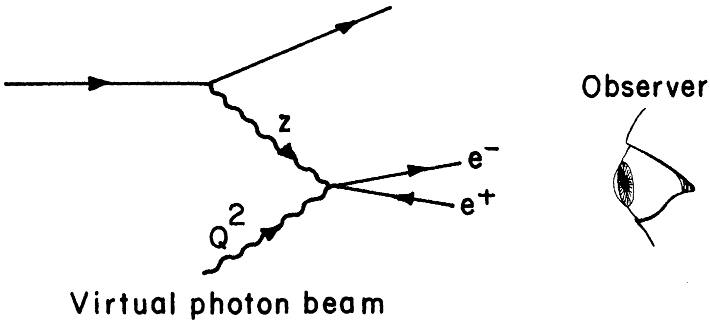


FIGURE 11. An observer "watches" a Feynman diagram. From Chris Quigg, *Gauge Theories of the Strong, Weak, and Electromagnetic Interactions* (New York, 1983), 231. Reproduced by kind permission of Perseus Books Publishers, a member of Perseus Books, L.L.C.

by including an observing eyeball alongside a Feynman diagram to emphasize which particles might be measured in an experiment (see fig. 11).

Unlike such heated discussions, no one ever even tried to push for a physical or literal interpretation of dual diagrams. In this way, the dual diagrams seem similar to the group-theory diagrams used by Murray Gell-Mann in his attempts to classify the new particles streaming out of the postwar accelerators (see fig. 12). Despite the tremendous classificatory simplification offered by the quark hypothesis, even Gell-Mann himself concluded from diagrams such as these that quarks were at most a "mathematical convenience," rather than robust physical particles, for the better part of the 1960s.[59]

From where, then, did these strong assertions and impassioned denials of the *reality* of Feynman diagrams come? Perhaps in answering this query we will find what was special and specific about Feynman diagrams for particle physicists during these decades, over and above the diagrams' strong pedagogical tradition and assimilability. These features, specific to the Feynman diagrams, may help to explain their persistence. Such special features, in other words, might have held the key to "realism" for these particle physicists at midcentury.

One locus to consider is the inundation of particle physicists in exactly this period with nuclear emulsion and bubble chamber photographs. It had been the "zoo" of unanticipated particles pouring out of the postwar accelerators, and captured photographically in bubble chambers, that had first thrust quantum field theory into turmoil and motivated many to pursue an autonomous *S*-matrix program. To particle physicists in the 1950s and 1960s, these photographs were simply inescapable: photos were published with articles in the *Physical Review*, on the covers of *Physics Today*, cataloged in huge "atlases," reprinted on the dust jackets and fron-

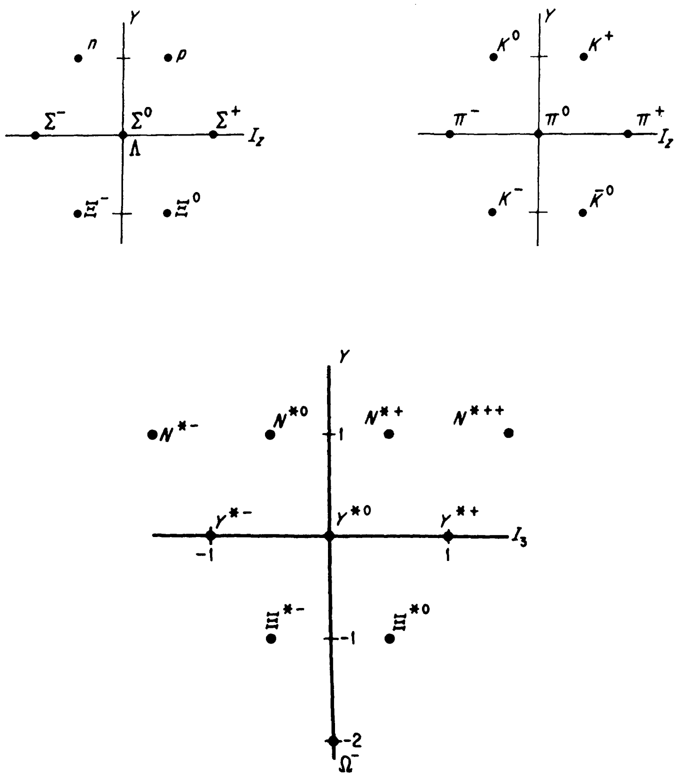


FIGURE 12. Classification of strongly interacting particles according to group-theory representations. Murray Gell-Mann argued from diagrams such as these that the particles could be classified simply on the hypothesis of three constituent quarks. From W. R. Frazer, *Elementary Particles* (Englewood Cliffs, N.J., 1966), 65, 95. Reproduced by kind permission of Prentice-Hall.

tispieces of textbooks and popular books, and pictured on slides for public lectures. Even theoretical physicists with little direct connection to the experimental groups producing the pictures were awash in these photographs and their frequent reprintings.[60]

Moreover, there developed in this period a highly schematized tradition of reconstructing particles' paths, as photographed with the new detectors. These stick-figure reconstructions appeared with great frequency during the early 1960s in textbooks and lecture notes on particle physics. While the nuclear emulsions photographs were often published with only minimal lines and arrows superimposed, bubble chamber photographs were usually published alongside stick-figure reconstructions of the specific events of interest (see fig. 13).[61] Other times, physicists sim-

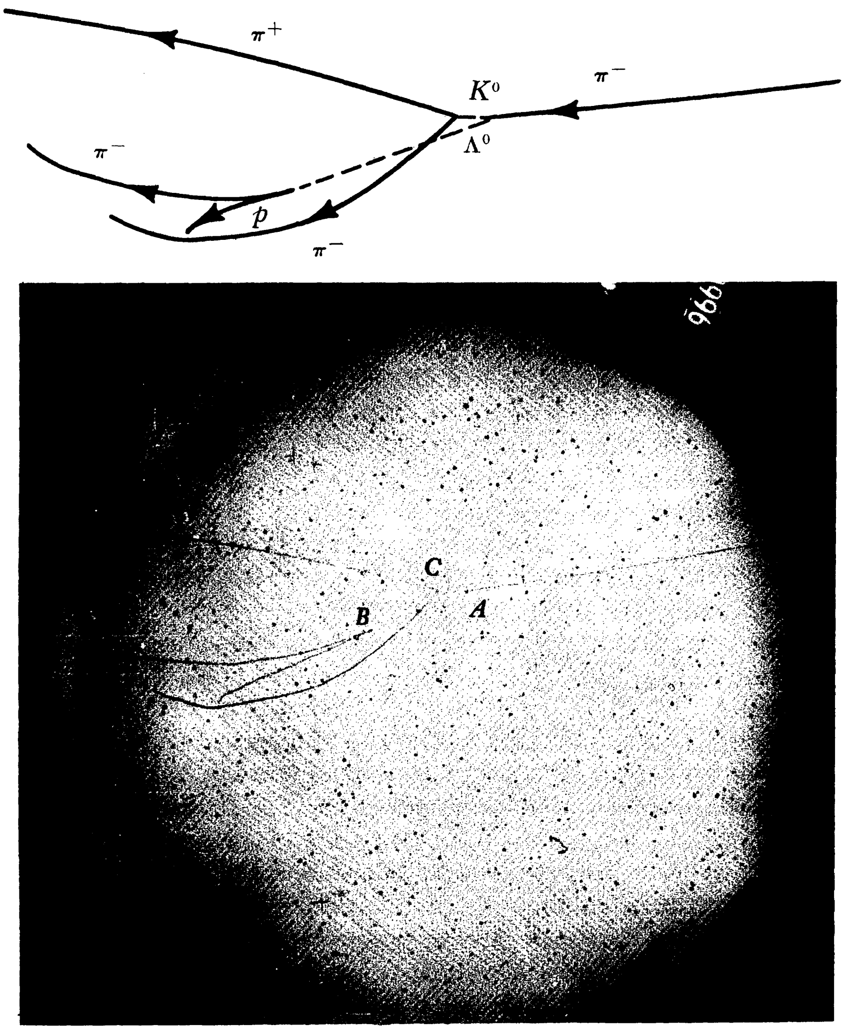


Figure 6.2. Examples of V-shaped tracks characteristic of "strange-particle" decays. **At *B*, a neutral lambda decays into a proton and a negative pion. At *C*, a neutral kaon decays into oppositely charged pions. At point *A*, a negative pion entering the chamber from the right struck a proton in the bubble chamber and produced the two strange particles according to the reaction,**

$$\pi^- + p \rightarrow \Lambda^0 + K^0.$$

FIGURE 13. Bubble chamber photograph together with schematic reconstruction. From K. W. Ford, *The World of Elementary Particles* (New York, 1963), 176. Reproduced by kind permission of Dr. Kenneth Ford.

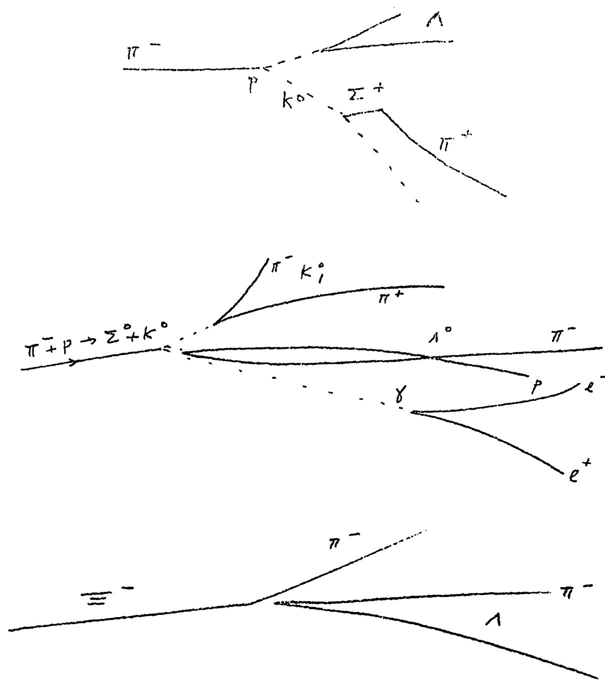


FIGURE 14. Freehand reconstruction of bubble chamber photographs. From R. Levi Setti, *Elementary Particles* (Chicago, 1963), 52, 60. Reproduced by kind permission of the University of Chicago Press.

ply sketched these line-drawing reconstructions, freehand, in their lecture notes and textbooks (see fig. 14).[62] At least one textbook introduced Feynman diagrams directly between these photographs and their line-drawing reconstructions, tacitly placing Feynman diagrams within a continuous series of visual evidence about real particles' behavior.[63]

Just as few physicists made explicit comparisons of Feynman diagrams with Minkowski diagrams during this period, fewer still made any claim that what was pictured on Feynman diagrams and in these schematic bubble chamber reconstructions were "the same thing." Yet, as before, paying particular attention to the specific visual schemata suggests some possibilities for connections. These bubble chamber reconstructions were built from two key ingredients: vertices and propagation lines. The Feynman and Feynman-like diagrams that were taken over into *S*-matrix theory were *not* the high-order loop corrections (for which the diagrams had first been invented, in their quantum electrodynamics days) but rather *lowest-order* and, most frequently, *single-particle exchange* diagrams. And what were the "visual ingredients" of these particular classes of Feynman diagrams? Nothing but vertices and propagation lines.

The Feynman diagrams most employed by the *S*-matrix theorists, and those employed by all particle theorists to introduce students to the diagrammatic apparatus in the first place, were strikingly similar to the most heavily relied upon evidence of actual particles and their interactions at this same time. The association of "realism" with Feynman diagrams in the 1950s and 1960s, based on their simple similarity to "real" photographs of "real" particles, helped the Feynman diagrams to stand out for many physicists. Unlike dual diagrams, Feynman diagrams could be read as more immediately related to real particles and processes and, hence, less bound up within a particular, abstract theory. No one had to proclaim that Feynman diagrams were "the same" as bubble chamber photographs, or their stylized reconstructions, for visual, representational affiliations to be made. And here the contrast with the dual diagrams is perhaps most clear (compare figs. 2–3, 10, 13–15).

Conclusions

Ernst Gombrich puzzled over the persistence of representational styles in his *Art and Illusion*. "Even after the development of naturalistic art," he wrote, "the vocabulary of representation shows a tenacity, a resistance to change, as if only a picture seen could account for a picture painted. The stability of styles in art is sufficiently striking to demand some such hypothesis of self-reinforcement."[64] The "tenacity" and "stability" of physicists' use of Feynman diagrams in the two decades after their introduction likewise calls for some explanation. The diagrams remained central to physicists' practice, even as they were reinterpreted, and as their original meanings and uses fell under sustained debate. By attending closely to the particular ways in which the diagrams were drawn and taught, and the visual similarities between the stick figures and other types of visual tools and traditions that the same community deployed at this same time, the diagrams' persistence becomes somewhat less puzzling.

In concluding, let me underscore some claims I am *not* making. I do not wish to assert that by drawing Feynman diagrams according to certain specific conventions, particle theorists "misunderstood" the conceptual distinctions between Minkowski diagrams and Feynman diagrams. Nor do I claim that physicists during this period had difficulty telling the difference between schematic bubble chamber reconstructions and lowest-order Feynman diagrams. My point here is instead that the high degree of overlap between the visual, representational schemata of the Feynman diagrams with those of Minkowski diagrams and of the bubble chamber track reconstructions might hold the key to why the diagrams lived on within various communities of physicists, even as the diagrams' original theoretical embeddings were challenged, loosened, or tossed away entirely.

A large portion of this staying power *did* likely derive from the diagrams' "ease

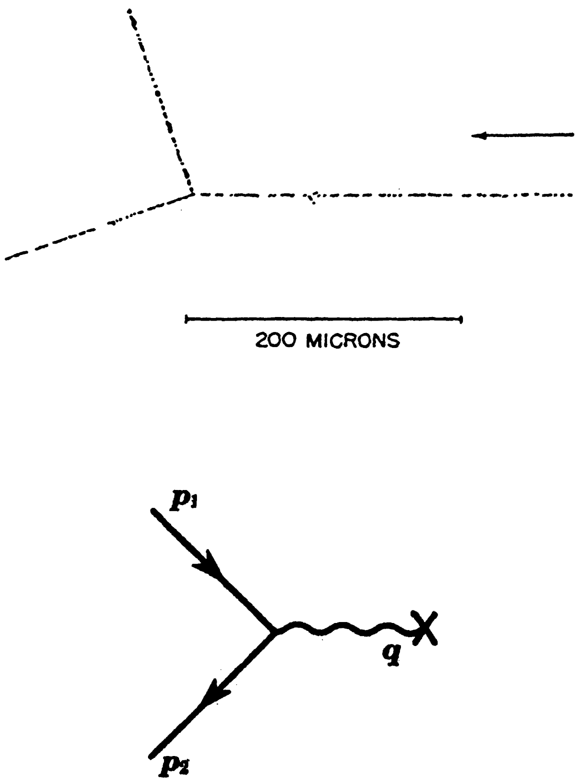


FIGURE 15. Top: Nuclear emulsion track. From G. Bernardini et al., "Nuclear Interaction of Pi-Minus Mesons," *Physical Review* 80 (1950): 924. © 1950 American Physical Society; reproduced by kind permission.
Bottom: Feynman diagram. From Schweber, Bethe, and de Hoffmann, *Mesons and Fields*, 1:224.

of acquisition," as Gombrich and Snyder might term it; this "ease" deriving in turn from the visual assimilation within the pedagogical tradition of Minkowski diagrams and the pictorial study of particles' propagation. Yet other visual devices put forward at this time, such as dual diagrams, were equally "easy to acquire," sharing an explicit tie to Kirchhoff's rules for elementary circuit theory. Despite this "habit-forming" potential, the dual diagrams faded quickly from view, while Feynman diagrams, also "easy to acquire" and "habit-forming," continued to define physicists' practice. Unlike the dual diagrams, Feynman diagrams could evoke, in an unspoken way, the scatterings and propagation of real particles, with "realist" associations for those physicists already awash in a steady stream of bubble chamber photographs, in ways that the dual diagrams simply did not encourage. Not all "habits," in other words, were treated the same way.

Following Goodman, we may agree that the Feynman diagrams' staying power did not derive from some inherent or essential features of the diagrams themselves, much less from the diagrams' ability to capture reality in some direct way; these diagrams were just as much "conventions" and "constructions" as any of the physicists' other visual tools, dual diagrams included. But stopping here, by noting only the Feynman diagrams' "conventional" and "constructed" status, would mean stopping short. Claiming only that "realism arises from habit" lacks discriminatory teeth and by itself provides no clues as to why Feynman diagrams were singled out as special by so many physicists at midcentury. These physicists could "read" Feynman diagrams against a confluence of specific visual associations. By following the patterns of physicists' doodling from undergraduate studies of Minkowski diagrams to freehand sketches of bubble chamber photographs, we begin to learn why physicists treated Feynman diagrams and dual diagrams quite differently; why the two types of diagrams mattered differently to people in various contexts; and why they were each attributed different meanings in different ways. Building upon work from both art history and science studies, then, we may understand how the bare, unadorned lines of the Feynman diagrams, in themselves such simple stick figures, came to define what it meant to *do* postwar particle physics, even as the competing meanings attributed to those same bare lines came and went.

Notes

This paper is dedicated in honor of Sam Schweber's seventieth birthday. Sam's voluminous contributions, as both physicist and historian, to understanding the roots and meaning of quantum field theory can claim very few rivals. It is a pleasure to thank, in addition to Sam, Ron Anderson, Mario Biagioli, Cathy Carson, Geoffrey Chew, James Cushing, James Elkins, Peter Galison, Tracy Gleason, Michael Gordin, Stephen Gordon, Naomi Oreskes, Elizabeth Paris, and Andrew Warwick for many enlightening discussions. I would also like to acknowledge the warm hospitality provided by the Office for History of Science and Technology at Berkeley, where most of the writing of this paper was done.

1. A preprint of Geoffrey Chew's talk at the 1961 La Jolla conference is quoted in James T. Cushing, *Theory Construction and Selection in Modern Physics: The S matrix* (New York, 1990), 143. See also Murray Gell-Mann, "Particle Theory from *S*-matrix to quarks," in *Symmetries in Physics, 1600–1980*, ed. by M. G. Doncel et al. (Barcelona, 1987), 479–97. This portion of Chew's unpublished talk was incorporated verbatim in the introduction to his 1961 textbook, *S-Matrix Theory of Strong Interactions* (New York, 1961), 1–

2. On rumors of Chew's baseball aspirations, see Stephen Gordon, "Strong Interactions: Particles, Passion, and the Rise and Fall of Nuclear Democracy" (A.B. honors thesis, Department of History of Science, Harvard University, 1998), 15. Many physicists recall Chew's unusual charisma during his campaign against quantum field theory; see John Polkinghorne, "Salesman of Ideas," in *A Passion for Physics: Essays in Honor of Geoffrey Chew*, ed. Carleton DeTar, J. Finkelstein, and Chung-I Tan (Singapore, 1985), 23–25, in addition to the interviews quoted in Gordon, "Strong Interactions."

2. Geoffrey Chew, "The Dubious Role of the Space-Time Continuum in Microscopic Physics," *Science Progress* 51 (1963): 529–39, here 538–39. The "mistress" motif was common at the time. Consider Marvin Goldberger's opening comments at the Twelfth Solvay Conference in 1961: "My own feeling is that we have learned a great deal from field theory. . . . I am quite happy to discard it as an old, but rather friendly, mistress who I would even be willing to recognize on the street if I should encounter her again"; M. L. Goldberger, "Theory and Application of Single Variable Dispersion Relations," in *The Quantum Theory of Fields*, ed. R. Stoop (New York, 1961), 179–96, here 179. For more on the use of such gendered language within high-energy physics, see Sharon Traweek, *Beamtimes and Lifetimes: The Worlds of High-Energy Physicists* (Cambridge, Mass., 1988), esp. chap. 3.

3. Ernst Gombrich, *Art and Illusion: A Study in the Psychology of Pictorial Representation* (Princeton, 1969 [1960]), 86, 89, 298. See also the classic study of linear perspective by Erwin Panofsky, *Perspective as Symbolic Form*, trans. Christopher S. Wood (New York, 1991 [1927]).

4. Nelson Goodman, *Languages of Art: An Approach to a Theory of Symbols* (Indianapolis, 1976 [1968]), 32, 37–38. Cf. Nelson Goodman, *Ways of Worldmaking* (Indianapolis, 1978).

5. Gombrich, *Art and Illusion*, 156, 313.

6. Ernst Gombrich, "Image and Code: Scope and Limits of Conventionalism in Pictorial Representation," in *Image and Code*, ed. Wendy Steiner (Ann Arbor, Mich., 1981), 11–42, here 16–17.

7. Joel Snyder, "Picturing Vision," in *The Languages of Images*, ed. W. J. T. Mitchell (Chicago, 1980), 219–46, here 223.

8. W. J. T. Mitchell, *Picture Theory: Essays on Verbal and Visual Representation* (Chicago, 1994), 352–53. See also W. J. T. Mitchell, *Iconology: Image, Text, Ideology* (Chicago, 1986), chap. 2.

9. Bruno Latour and Steve Woolgar, *Laboratory Life: The Construction of Scientific Facts*, 2d ed. (Princeton, 1986 [1979]), passim. See also *Picturing Power: Visual Depictions and Social Relations*, ed. Gordon Fyfe and John Law (New York, 1988); *Representation in Scientific Practice*, ed. Michael Lynch and Steve Woolgar (Cambridge, Mass., 1990); *Pictorial Representation in Biology*, ed. Peter Taylor and Ann Blum, published as a special issue of *Biology and Philosophy* 6 (1991); *Picturing Knowledge: Historical and Philosophical Problems Concerning the Use of Art in Science*, ed. Brian S. Baigrie (Toronto, 1996); and *Picturing Science, Producing Art*, ed. Caroline Jones and Peter Galison (New York, 1998). Two early articles within the history and sociology of science that pointed to the question of images and "visual languages" in science are Martin Rudwick, "The Emergence of a Visual Language for Geological Science, 1760–1840," *History of Science* 14 (1976): 149–95; and Michael Lynch, "Discipline and the Material Form of Images: An Analysis of Scientific Visibility," *Social Studies of Science* 15 (1985): 37–66. Many similar ques-

tions are raised by Arthur Miller in his study of early-twentieth-century physics; see Arthur Miller, *Imagery in Scientific Thought: Creating Twentieth-Century Physics* (Boston, 1984).

10. Cf. Alex Soojung-Kim Pang, "Visual Representation and Post-Constructivist History of Science," *Historical Studies in the Physical and Biological Sciences* 28 (1997): 139–71; James Elkins, "Art History and Images That Are Not Art," *Art Bulletin* 77 (1995): 553–72; and James Elkins, *The Domain of Images* (Ithaca, N.Y., 1999). Some roles of scientific illustrations and diagrams as heuristic, and often generative, metaphors have been explored in Rudwick, "Emergence of a Visual Language for Geological Science," as well as in James Griesemer and William Wimsatt, "Picturing Weismannism: A Case Study of Conceptual Evolution," in *What the Philosophy of Biology Is*, ed. M. Ruse (Dordrecht, 1989), 75–137; David Gooding, "Theory and Observation: The Experimental Nexus," *International Studies in the Philosophy of Science* 4 (1990): 131–48; Alberto Cambrosio, Daniel Jacobi, and Peter Keating, "Ehrlich's 'Beautiful Pictures' and the Controversial Beginnings of Immunological Imagery," *Isis* 84 (1993): 662–99; and Ursula Klein, "Techniques of Modeling and Paper-Tools in Classical Chemistry," in *Models as Mediators: Perspectives on Natural and Social Science*, ed. Mary Morgan and Margaret Morrison (New York, 1999), 146–67.
11. For more on quantum electrodynamics during the 1930s and 1940s, see especially Silvan S. Schweber, *QED and the Men Who Made It: Dyson, Feynman, Schwinger, and Tomonaga* (Princeton, 1994). See also Tian Yu Cao, *Conceptual Developments of Twentieth-Century Field Theories* (New York, 1997), part 2; *Early Quantum Electrodynamics: A Source Book*, ed. Arthur I. Miller (New York, 1994); Abraham Pais, *Inward Bound: Of Matter and Forces in the Physical World* (New York, 1986), chaps. 15–18; David Cassidy, "Cosmic Ray Showers, High Energy Physics, and Quantum Field Theories: Programmatic Interactions in the 1930s," *Historical Studies in the Physical Sciences* 12 (1981): 1–39; Peter Galison, *How Experiments End* (Chicago, 1987), chap. 3; Alexander Rueger, "Attitudes Towards Infinities: Responses to Anomalies in Quantum Electrodynamics, 1927–1947," *Historical Studies in the Physical and Biological Sciences* 22 (1992): 309–37; and Cathryn Carson, "The Peculiar Notion of Exchange Forces (II): From Nuclear Forces to QED, 1929–1950," *Studies in History and Philosophy of Modern Physics* 27 (1996): 99–131. For details of the organization of the Pocono Conference, see especially Schweber, *QED*, chap. 4.
12. Richard Feynman, "Pocono Conference," *Physics Today* 1, no. 2 (1948): 8–10; Richard Feynman, "The Theory of Positrons," *Physical Review* 76 (1949): 749–59; Richard Feynman, "Space-Time Approach to Quantum Electrodynamics," *Physical Review* 76 (1949): 769–89; and Richard Feynman, "The Development of the Space-Time View of Quantum Electrodynamics," *Science* 153 (1966): 699–708. See also *Selected Papers on Quantum Electrodynamics*, ed. Julian Schwinger (New York, 1958); Schweber, *QED*, chap. 8; and Peter Galison, "Feynman's War: Modeling Weapons, Modeling Nature," *Studies in History and Philosophy of Modern Physics* 29 (1998): 391–434.
13. F.J. Dyson, "The Radiation Theories of Tomonaga, Schwinger, and Feynman," *Physical Review* 75 (1949): 486–502, and F.J. Dyson, "The *S* Matrix in Quantum Electrodynamics," *Physical Review* 75 (1949): 1736–55. See also F.J. Dyson, "Old and New Fashions in Field Theory," *Physics Today* 18 (June 1965): 21–24, and Schweber, *QED*, chap. 9. F.J. Dyson recounts his friendship with Feynman in *Disturbing the Universe* (New York, 1979), 53–68.

14. A "virtual particle" is one that does not obey Albert Einstein's famous relation between energy (E) and mass (m), $E = mc^2$, where c is the speed of light. Instead, virtual particles "borrow" excess energy and momentum for very short periods of time, as allowed by Werner Heisenberg's uncertainty principle. A "photon" is a quantum, or discrete particle, of light. According to quantum field theory, *all* interactions arise from the exchange of virtual particles.
15. A "positron" is a particle sharing all of the properties of an electron, but having a positive electric charge instead of a negative one. Pairs of virtual electrons and positrons may therefore be created or annihilated without changing the total electric charge of a system. The ideas of pair creation and annihilation predate Paul Dirac's famous work on the topic; see Joan Bromberg, "The Concept of Particle Creation Before and After Quantum Mechanics," *Historical Studies in the Physical Sciences* 7 (1976): 161–91.
16. Richard D. Mattuck, *A Guide to Feynman Diagrams in the Many-Body Problem* (New York, 1976 [1967]), 120. Mattuck's text developed the use of Feynman diagrams for applications in solid-state theory, rather than in high-energy particle theory.
17. Robert Seidel, "Accelerating Science: The Postwar Transformation of the Lawrence Radiation Laboratory," *Historical Studies in the Physical Sciences* 13 (1983): 375–400; Robert Seidel, "Accelerators and National Security: The Evolution of Science Policy for High-Energy Physics, 1947–1967," *History and Technology* 11 (1994): 361–92; John Heilbron and Robert Seidel, *Lawrence and His Laboratory* (Berkeley, 1989); Adrienne Kolb and Lillian Hoddeson, "The Mirage of the 'World Accelerator for World Peace' and the Origins of the SSC, 1953–1983," *Historical Studies in the Physical and Biological Sciences* 24 (1993): 101–24; Peter Galison, *Image and Logic: A Material Culture of Microphysics* (Chicago, 1997).
18. See *The Birth of Particle Physics*, ed. Laurie Brown and Lillian Hoddeson (New York, 1983); Andrew Pickering, *Constructing Quarks: A Sociological History of Particle Physics* (Chicago, 1984), chap. 3; *Pions to Quarks: Particle Physics in the 1950s*, ed. Laurie Brown, Max Dresden, and Lillian Hoddeson (New York, 1989); and John C. Polkinghorne, *Rochester Roundabout: The Story of High Energy Physics* (New York, 1989).
19. The reason was because the coupling constant for the strong interactions appeared to be large, in the range $g^2 = 7 - 57$, unlike the small coupling constant of quantum electrodynamics, $e^2 = {}^1/_{137}$. With $g^2 >> 1$, more complicated diagrams, containing more vertices and hence more factors of g^2, would overwhelm the simpler diagrams, instead of contributing smaller and smaller correction terms; see the "Theoretical Session" in *Proceedings of the Fourth Annual Rochester Conference on High Energy Nuclear Physics*, ed. H. P. Noyes et al. (Rochester, N.Y., 1954), 26–40; Pais, *Inward Bound*, 482–85; and Polkinghorne, *Rochester Roundabout*, 40–41.
20. Prominent examples of new uses to which the diagrams were put include work in meson theory, single and double dispersion relations, polology, and the bootstrap hypothesis. These are each explored further in David Kaiser, "Feynman Diagrams in and out of Field Theory 1948—66," unpublished manuscript.
21. Chew, *S-Matrix Theory of Strong Interactions*; Geoffrey Chew, "Nuclear Democracy and Bootstrap Dynamics," in *Strong-Interaction Physics: A Lecture Note Volume*, by Maurice Jacob and Geoffrey Chew (New York, 1964), 103–52; Geoffrey Chew, *The Analytic S Matrix: A Basis for Nuclear Democracy* (New York, 1966). See also Cushing, *Theory Construction*; Tian Yu Cao, "The Reggeization Program 1962–1982: Attempts at Reconciling

Quantum Field Theory with *S*-Matrix Theory," *Archive for the History of the Exact Sciences* 41 (1991): 239–82. On Chew's uses of Feynman diagrams within *S*-matrix theory, see David Kaiser, "Do Feynman Diagrams Endorse a Particle Ontology? The Roles of Feynman Diagrams in *S*-Matrix Theory," in *Conceptual Foundations of Quantum Field Theory*, edited by Tian Yu Cao (New York, 1998), 343–56, and Kaiser "Feynman Diagrams in and out of Field Theory."

22. Chew, *S-Matrix Theory of Strong Interactions*, 3; cf. vii–viii, 15–16, 23–25. Feynman diagrams, and their *S*-matrix theory generalizations in "Landau" and "Cutkosky diagrams," appear with great frequency throughout Chew's own textbooks and those of his former students and collaborators; see, ibid., 16–17, 24–26, 38, 42–43, 75, 82–83; R. Omnès and M. Froissart, *Mandelstam Theory and Regge Poles* (New York, 1963), 76, 82–83, 85–86, 88, 114, 120–21; Steven Frautschi, *Regge Poles and S-Matrix Theory* (New York, 1963), 70–72, 93, 174, 192; and William Frazer, *Elementary Particles* (Englewood Cliffs, N.J., 1966), 51, 103, 105, 112–15, 124, 128, 131, 134, 154, 161. They similarly pervade the dissertations written by Chew's graduate students. The most notable generative uses to which Feynman diagrams were put by the *S*-matrix theorists include "nuclear democracy" and the "hadron bootstrap"; see Kaiser, "Do Feynman Diagrams Endorse," and Kaiser, "Feynman Diagrams in and out of Field Theory"; see also Geoffrey Chew, "Particles as *S*-Matrix Poles: Hadron Democracy," in *Pions to Quarks*, 600–607, and Michael Moravcsik, "Thirty Years of One-Particle Exchange," in *A Passion for Physics*, 26–34.
23. William R. Frazer, "The Analytic and Unitary *S* Matrix," in *A Passion for Physics*, 1–8. Figure 6, taken from Frazer's toast, should be compared with the table in figure 1.
24. Dyson commented years later, "The calculation I did for Hans [Bethe], using the orthodox theory, took me several months of work and several hundred sheets of paper. Dick [Feynman] could get the same answer, calculating on the blackboard, in half an hour"; Dyson, *Disturbing the Universe*, 54; cf. Pais, *Inward Bound*, 452.
25. Julian Schwinger, "Renormalization Theory of Quantum Electrodynamics: An Individual View," in *Birth of Particle Physics*, 329–53, here 343.
26. Peter Taylor and Ann Blum noted that such a focus on "conventions of pictorial representation in science" has been "insufficiently explored" in the growing literature on scientific images and visualization; see Peter Taylor and Ann Blum, "Pictorial Representation in Biology," *Biology and Philosophy* 6 (1991): 125–34, here 129; see also 130–32. For an intriguing example of such an attention to conventions, see Samuel Edgerton, "Galileo, Florentine 'Disegno,' and the 'Strange Spottednesse' of the Moon," *Art Journal* 44 (1984): 225–32.
27. Dyson, "Radiation Theories," 495. On the 1950s craze for "paint by numbers" kits, see Karal Ann Marling, *As Seen on TV: Visual Culture in the 1950s* (Cambridge, Mass., 1994), chap. 2.
28. Dyson, "Radiation Theories," 495. See also Dyson, "The *S* Matrix in Quantum Electrodynamics," 1738. Strictly for typographical ease, Dirac-conjugate fields are denoted here with an underline rather than an overline.
29. Silvan Schweber, Hans Bethe, and Frederic de Hoffmann, *Mesons and Fields*, (White Plains, N.Y., 1955), 1:219–20, 225. As noted in the preface, volume 1 was written primarily by Schweber. Cf. Silvan Schweber, *An Introduction to Relativistic Quantum Field Theory* (New York, 1961), 448.
30. F. Mandl, *Introduction to Quantum Field Theory* (New York, 1959), chaps. 11 and 14, in

particular 73–74, 96–97. See also H. Umezawa, *Quantum Field Theory* (New York, 1956), 227.

31. Kenneth W. Ford, *The World of Elementary Particles* (New York, 1963), 199, 200.
32. A. I. Akhiezer and V. B. Berestetskii, *Quantum Electrodynamics*, trans. G. M. Volkoff (New York, 1965 [1959]), 308.
33. Compare Gombrich's discussion in *Art and Illusion*, chap. 5.
34. Leonard Schiff to Edward Teller, 26 May 1953, in Raymond Thayer Birge, *Correspondence and Papers*, box 25, folder "Schiff, Leonard Isaac, 1915–1971." The Birge collection is call number 73/79c in the Bancroft Library, University of California at Berkeley. Gian Carlo Wick called Feynman's techniques "widely used" in an article from 1950: "The Evaluation of the Collision Matrix," *Physical Review* 80 (1950): 268–72, here 268.
35. See Peter Galison, "Minkowski's Space-Time: From Visual Thinking to the Absolute World," *Historical Studies in the Physical Sciences* 10 (1979): 85–121. Stanley Goldberg charts the incorporation of special relativity into the curricula for undergraduate and graduate physics instruction in the United States between 1920 and 1980 in *Understanding Relativity: Origin and Impact of a Scientific Revolution* (Boston, 1984), part 3; see esp. 277–93.
36. See the interview between Feynman and Robert Crease and Charles Mann, quoted in Robert Crease and Charles Mann, *The Second Creation: Makers of the Revolution in Twentieth-Century Physics* (New York, 1986), 137–38. Cf. Schweber, *QED*, 436–45; Pais, *Inward Bound*, 452; and James Gleick, *Genius: The Life and Times of Richard Feynman* (New York, 1992), 255–61.
37. Feynman, "Theory of Positrons," 749–51, and Feynman, "Space-Time Approach," 775.
38. Schweber, Bethe, and de Hoffmann, *Mesons and Fields*, 1:62.
39. J. M. Jauch and F. Rohrlich, *The Theory of Photons and Electrons* (Cambridge, Mass., 1955), 147.
40. Schweber, Bethe, and de Hoffmann, *Mesons and Fields*, 1:219–21; Jauch and Rohrlich, *Theory of Photons and Electrons*, 146–50; H. Umezawa, *Quantum Field Theory*, 227–29; F. Mandl, *Introduction to Quantum Field Theory*, 73, 94–104; N. N. Bogoliubov and D. V. Shirkov, *Introduction to the Theory of Quantized Fields*, trans G. M. Volkoff (New York, 1959), 235–44; J. Hamilton, *The Theory of Elementary Particles* (Oxford, 1959), 238–48; Schweber, *Introduction to Relativistic Quantum Field Theory*, 448–53; James Bjorken and Sidney Drell, *Relativistic Quantum Fields* (New York, 1965), 185–87; Akhiezer and Berestetskii, *Quantum Electrodynamics*, 307–16; and Stephen Gasiorowicz, *Elementary Particle Physics* (New York, 1966), 134–36.

    Note that these conventions do not always hold in more recent textbooks, some of which begin discussion of Feynman diagrams in the momentum-space representation and often have the time axis running horizontally instead of vertically; see Claude Itzykson and Jean-Bernard Zuber, *Quantum Field Theory* (New York, 1980), 226–35, and chap. 6; Pierre Ramond, *Field Theory: A Modern Primer* (Reading, 1981), chap. 4; and Lowell S. Brown, *Quantum Field Theory* (New York, 1992), chap. 3.
41. See Schweber, Bethe, and de Hoffmann, *Mesons and Fields*, 1:240–41; James Bjorken and Sidney Drell, *Relativistic Quantum Mechanics* (New York, 1964), 118, 122; and Gasiorowicz, *Elementary Particle Physics*, 136.

42. See, e.g., J. Ashkin, T. Auerbach, and R. Marshak, "Note on a Possible Annihilation Process for Negative Protons," *Physical Review* 79 (1950): 266–71; M. N. Rosenbluth, "High Energy Elastic Scattering of Electrons on Protons," *Physical Review* 79 (1950): 615–19; K. A. Brueckner, "The Production of Mesons by Photons," *Physical Review* 79 (1950): 641–50; R. Jost, J. M. Luttinger, and M. Slotnick, "Distribution of Recoil Nucleus in Pair Production by Photons," *Physical Review* 80 (1950): 189–96; M. Peshkin, "Scattering and Absorption of Scalar and Pseudoscalar Mesons by Nucleons," *Physical Review* 81 (1951): 425–29.
43. Feynman, "Space-Time Approach," 772–73; several momentum-space diagrams continue using these Minkowski-like conventions, e.g., those on 774–75, 789.
44. See, e.g., Schweber, Bethe, and de Hoffmann, *Mesons and Fields*, 1:78, 153, 155, 219–20; Mandl, *Introduction to Quantum Field Theory*, 20, 73, 99–101; Robert B. Leighton, *Principles of Modern Physics* (New York, 1959), 672, 674–78; Paul Roman, *Theory of Elementary Particles* (Amsterdam, 1960), 205; Bjorken and Drell, *Relativistic Quantum Mechanics*, 80, 98; and Richard Feynman, *Quantum Electrodynamics: A Lecture Note and Reprint Volume* (New York, 1961), 89, 96, and 123.
45. When horizontal lines did appear in these early Feynman diagrams, they often denoted the nonpropagating presence of a classical, external potential for applications to semi-classical Coulomb scattering. In these diagrams, the lines for the physically propagating electrons and positrons were inclined according to Minkowski-diagram conventions; see, e.g., Schweber, Bethe, and de Hoffmann, *Mesons and Fields*, 1:220–21; Mandl, *Introduction to Quantum Field Theory*, 117; Bjorken and Drell, *Relativistic Quantum Mechanics*, 124. There is also a clear difference between styles of Feynman diagrams throughout Bjorken and Drell's twin textbooks from 1964–65. When introducing a new kind of decay or interaction for the first time, the Feynman diagrams are often most "Minkowski-like," whereas when deploying higher-order diagrams to track loop-corrections in the service of abstract renormalization theory, the diagrams are far more "stylized," with several rounded photon lines, and make no use of inclined lines for exchanges; compare Bjorken and Drell, *Relativistic Quantum Mechanics*, 216–17, 248, 251, 261, 266, 273–75, with Bjorken and Drell, *Relativistic Quantum Fields*, 285–93, 295–96, 301.
46. Jauch and Rohrlich, *Theory of Photons and Electrons*, 149.
47. Ernest Henley and Walter Thirring, *Elementary Quantum Field Theory* (New York, 1962), 146. This is the only source I have found that explicitly raised Niels Bohr's original objection to Feynman, that is, that classical paths could not be attributed to quantum particles. Thirring was at the time the director of the Institute for Theoretical Physics at the University of Vienna; his Bohr-styled caution here may be a remnant of the Continental physicists' deep-going absorption of the Copenhagen interpretation of quantum mechanics, which, during the 1920s, had famously forsaken attempts to visualize quantum phenomena in space and time; see Miller, *Imagery in Scientific Thought*; and Catherine Chevalley, "Physics as an Art, The German Tradition and the Symbolic Turn in Philosophy, History of Art, and Natural Science in the 1920s," in *The Elusive Synthesis: Aesthetics and Science*, ed. by A. I. Tauber (Boston, 1996), pp. 227–49. I would like to thank Cathy Carson for raising this interesting point, and Edward MacKinnon for bringing Chevalley's article to my attention.
48. Mattuck, *Guide to Feynman Diagrams*, chaps. 2–3; Ford, *World of Elementary Particles*, 191–201; M. Stanley Livingston, *Particle Physics: The High-Energy Frontier* (New York, 1968),

204–5; Richard Feynman, *QED: The Strange Theory of Light and Matter* (Princeton, 1985), chap. 3.

49. Lev Landau, "On Analytic Properties of Vertex Parts in Quantum Field Theory," *Nuclear Physics* 13 (1959): 181–92, here 184, 186, 188; John C. Polkinghorne, "The Analytic Properties of Perturbation Theory," in *Dispersion Relations: Scottish Universities' Summer School, 1960*, ed. G. R. Screaton (New York, 1961), 65–93; J. C. Taylor, "Analytic Properties of Perturbation Expansions," *Physical Review* 117 (1960): 261–65; L. B. Okun and A. P. Rudik, "On a Method of Finding Singularities of Feynman Graphs," *Nuclear Physics* 15 (1960): 261–88; R. Eden et al., *The Analytic S-Matrix* (Cambridge, 1966), 60–62, 73–76, 104–8. Landau first introduced dual diagrams in his 1959 article; for more on Landau and his work, see esp. Karl Hall, *Purely Practical Revolutionaries: A History of Stalinist Theoretical Physics* (Ph.D. dissertation, Harvard University, 1999), chaps. 4–9.
50. An "analytic" function is, loosely speaking, a function that behaves "smoothly" enough that, given its value at a particular point, it may be evaluated anywhere else within a certain domain. This domain is called the function's domain of analyticity. Charting these domains of analyticity became central to the *S*-matrix program; see Chew, *S-Matrix Theory of Strong Interactions*; Eden et al., *Analytic S-Matrix*, chap. 2; and Cushing, *Theory Construction*, chap. 5. The insufficiency of Feynman diagrams alone to determine these analytic properties (especially in the face of "anomalous thresholds") was discussed in J. C. Polkinghorne, "Analyticity and Unitarity, II," *Il Nuovo Cimento* 25 (1962): 901–11; and D. B. Fairlie et al., "Singularities of the Second Type," *Journal of Mathematical Physics* 3 (1962): 594–602.
51. Compare with James Bjorken's development in his 1959 dissertation of "reduced graphs" (first introduced by Landau) to study these functions' analytic properties; see James Bjorken and Sidney Drell, *Relativistic Quantum Fields*, chap. 18. The historical point is that Feynman diagrams alone were insufficient for all of these tasks. For more on the "reduced graphs," see Kaiser, "Feyman Diagrams in and out of Field Theory."
52. See Polkinghorne, "Analytic Properties of Perturbation Theory," 83; Eden et al., *Analytic S-Matrix*, chap. 2. Bjorken extended the analogy to elementary circuit theory quite a bit further, when relating the closed loops of Feynman diagrams and "reduced graphs" to Gustav Kirchhoff's treatment of closed circuits; see Bjorken and Drell, *Relativistic Quantum Fields*, 220–26.
53. I borrow the convenient term "paper tools" from Ursula Klein, "Techniques of Modeling and Paper-Tools in Classical Chemistry." See also the recent work by Andrew Warwick, "Writing It Out for Routh: Learning Mathematical Physics in Victorian Cambridge," unpublished manuscript. I would like to thank both Klein and Warwick for sharing copies of their work prior to publication.
54. Rudwick, "The Emergence of a Visual Language for Geological Science"; David Gooding, "How Do Scientists Reach Agreement About Novel Observations?" *Studies in History and Philosophy of Science* 17 (1986): 205–30; David Gooding, "Mapping Experiment as a Learning Process: How the First Electromagnetic Motor Was Invented," *Science, Technology, and Human Values* 15 (1990): 165–201; David Gooding, "Imaginary Science," *British Journal for Philosophy of Science* 45 (1994): 1029–46; Nancy Nersessian, "Reasoning from Imagery and Analogy in Scientific Concept Formation," *Philosophy of Science Association* 1 (1988): 41–47; François Dagognet, *Tableaux et langages de la chimie* (Paris, 1969); Klein, "Techniques of Modeling and Paper-Tools in Classical Chemistry"; Mary Jo Nye, *From Chemical Philosophy to Theoretical Chemistry* (Berkeley, 1993),

chap. 4; Christopher Ritter, "Re-presenting Science: Frankland, Brodie, Education, and Practice in Nineteenth-Century Chemistry," talk presented at the 1997 History of Science Society annual meeting; Robert Brain and M. Norton Wise, "Muscles and Engines: Indicator Diagrams and Helmholtz's Graphical Methods" (in English), in *Universalgenie Helmholtz: Rueckblick nach 100 Jahren*, ed. Lorenz Krueger (Berlin, 1994), 124–49; Cambrosio, Jacobi, and Keating, "Ehrlich's 'Beautiful Pictures' "; and Naomi Oreskes, *The Rejection of Continental Drift* (New York, 1999), chap. 6. See also Ludwik Fleck, *Genesis and Development of a Scientific Fact*, trans. F. Bradley and T.J. Trenn (Chicago, 1979 [1935]), 125–45.

55. Dyson, "Radiation Theories," 496. Emphasis added.
56. Gasiorowicz, *Elementary Particle Physics*, 134.
57. Mattuck, *Guide to Feynman Diagrams*, 88. Emphasis in original.
58. F.A. Kaempffer, *Concepts in Quantum Mechanics* (New York, 1965), 209. Emphasis in original. Sixty years after Niels Bohr thought he had nailed the coffin shut on visualization in quantum physics, his former student Victor Weisskopf explained in his textbook, "one should not be afraid to use [Feynman] diagrams," regardless of the "extent one can ascribe physical reality to the diagrams"; Kurt Gottfried and Victor Weisskopf, *Concepts of Particle Physics* (New York, 1984), 1:40.
59. See Pickering, *Constructing Quarks*, chap. 4. The group-theory diagrams included in Gasiorowicz's 1966 textbook, with their solid lines making closed geometrical shapes, show an even stronger resemblance to the dual diagrams of Polkinghorne's *S*-matrix work; see Gasiorowicz, *Elementary Particle Physics*, chap. 18.
60. See, e.g., G. Bernardini et al., "Nuclear Interaction of Pi-Minus Mesons," *Physical Review* 80 (1950): 924–25; E. Pickup and L. Voyvodic, "Cosmic-Ray Nucleon-Nucleon Collisions in Photographic Emulsions," *Physical Review* 82 (1951): 265; the cover of *Physics Today* 8 (August 1955); the dust jacket of William R. Frazer, *Elementary Particles*, and of C. N. Yang, *Elementary Particles: The Vanuxem Lectures* (Princeton, 1962). The tradition of photographing particle tracks extends back to the turn of the century with C. T. R. Wilson's cloud chamber; but it was only after World War II that such photographs were produced so rapidly and in such volume, by the hundreds of millions, in European and American bubble chambers. On the long history of this "image tradition" within twentieth-century physics, see Galison, *Image and Logic*. For more on the atlases of cloud chamber and bubble chamber photographs, see also Galison, "Judgment against Objectivity," in Jones and Galison, *Picturing Science, Producing Art*, 327–59.
61. See, e.g., the undergraduate textbooks by Leighton, *Principles*, 642–48, 683–87; and Y. V. Novozhilov, *Elementary Particles* (Delhi, 1961), 40, 59, 61, 97, 102, 111, 133–34, 137, 154, 172. See also the popular books by C. N. Yang, *Elementary Particles*, 22, 24, 30, 33, 45, 47; Ford, *World of Elementary Particles*, 20–21, 24–25, 176, 182–83; Robert Gouiran, *Particles and Accelerators*, trans. W. F. G. Crozier (New York, 1967), 71, 82–83, 85–87, 104–5.
62. See, e.g., Novozhilov, *Elementary Particles*, 139, 148, 156, and 176; Riccardo Levi Setti, *Elementary Particles* (Chicago, 1963), 102, 109–10; J. Hamilton, *Elementary Introduction to Elementary Particle Physics*, lectures delivered at the Niels Bohr Institute and NORDITA, 1964/5, published in mimeographed form by NORDITA. See also Livingston, *Particle Physics*, 159, 164, 191.
63. Leighton, *Principles*, 642–48, 683–87. Michael Lynch has highlighted the practice of publishing photographs of biological cells together with sparse, line-drawing recon-

structions as a means of bolstering the ontological authority of the latter, while bringing epistemological clarity to the former; see Michael Lynch, "Science in the Age of Mechanical Reproduction: Moral and Epistemic Relations Between Diagrams and Photographs," *Biology and Philosophy* 6 (1991): 205–26.

64. Gombrich, *Art and Illusion*, 315; see also his introduction, 3–30.