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# Pictures and pedagogy: The role of diagrams in Feynman's early lectures

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ABSTRACT

This paper aims to give a substantive account of how Feynman used diagrams in the first lectures in which he explained his new approach to quantum electrodynamics. By critically examining unpublished lecture notes, Feynman's use and interpretation of both "Feynman diagrams" and other visual representations will be illuminated. This paper will discuss how the morphology of Feynman's early diagrams were determined by both highly contextual issues, which molded his images to local needs and particular physical characterizations, and an overarching common diagrammatic style, which facilitated Feynman's movement between different diagrams despite their divergent forms and significance.



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## 1. Introduction

To many, the name Richard Feynman (1918–1988) immediately conjures up images of his eponymous diagrams. In the field of the history and philosophy of science, investigations into the origins, uses, and interpretations of Feynman's simple yet immensely powerful diagrammatic representations of subatomic events have experienced a moderate but notable surge in interest as of late. Philosophers such as James Brown and Letitia Meynell have discussed the question of what, precisely, Feynman diagrams represent.[1] While David Kaiser has also addressed the question of representation, his work on Feynman diagrams has been primarily historical, as his book *Drawing Theories Apart* focuses mainly on the adoption ("dispersion") of Feynman diagrams and the factors and mechanisms which enabled this.[2] Most recently, Adrian Wüthrich has written on the early origins of Feynman's diagrams, tracing their development from Feynman's early "path counting" to Freeman Dyson's formalizing "intervention".[3]

Despite the excellent work contextualizing Feynman diagrams within Feynman's theoretical struggles, the post-doctoral and international academic systems, and the philosophical questions surrounding representation, few scholars have opted to view Feynman diagrams as one of a number of visual techniques produced by Richard Feynman. By singling out "Feynman diagrams" at the expense of the numerous other types of diagrams used by Feynman, the insight one gains into the role of diagrams in scientific thought and the nature of visual reasoning is unnecessarily narrowed.

This paper aims to step back and address the plurality of diagrams produced by Feynman, "Feynman diagrams" included, within their historical and textual context. In particular, I shall give a substantive account of how Feynman used diagrams in the first lectures in which he was tasked with explaining his new approach to quantum electrodynamics, which he delivered at the University of Michigan in 1949. In observing Feynman's refusal to restrict himself to one specific style of diagram, namely the generalized interactions we commonly refer to as "Feynman diagrams", we are confronted with the question of why Feynman employed a spectrum of diagrams rather than a single type. While we will come to understand this plurality in terms of local pedagogical decisions, we shall nevertheless see how, despite differences in both the appearance and significance of these diagrams, Feynman relied on visual commonalities to move between various diagrams with ease.

## 2. Some historical background to Feynman's "new approach"

This work will investigate the role of Feynman's diagrams in his early talks. As we shall see, Feynman used a variety of

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[1] Brown (1996), Meynell (2008).

[2] Kaiser (2000, 2005).

[3] Wüthrich (2010). Of course, some older, but still highly valuable, historical works also exist, most notably Sam Schweber's "Feynman and the Visualization of Space–Time Processes" and his subsequent book, *QED*. Schweber (1986, 1994).

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diagrams to help communicate and explain his ''new approach'' to QED, both in its fullest formation and in for more simplified cases, as well as to facilitate the calculation of probability amplitudes for quantum interactions. However, before we begin exploring how Feynman used diagrams in his lectures we must first briefly present the historical background to these talks.

Beginning in the early 1940s, Feynman had been working on a way to physically understand and mathematically describe time-delayed interactions between relativistic particles. His doctoral thesis, completed in 1942 under Archibald Wheeler, provided a method for describing non-relativistic electrodynamic interactions in terms of a quantum analog of the classical principle of least action. This approach was well-suited to Feynman's method as it involved considering interactions in terms of advanced as well as retarded waves, advanced waves being waves transmitted from the future to the past. This approach allowed Feynman to describe quantum interactions without invoking a Hamiltonian, a description that would not have been possible given Feynman's use of advanced waves.[4]

While Feynman was ultimately unable to successfully apply this approach to the three-dimensional Dirac equation, several of the general themes characterized by Feynman's methodology would come to frame his ''new approach'' to QED, which he adopted in the late 1940s.[5] For one, Feynman's new approach still involved future events influencing past ones, as he characterized positrons as electrons traveling backwards in time. The suggestion that positrons are backwards-traveling electrons, originally proposed by Wheeler in 1940, would become one of Feynman's most novel contributions to the field of particle physics.

Feynman's mathematical approach, while different from his original path integral method, continued to eschew considering the Hamiltonian form of wave equations. Instead of directly solving the Schrödinger or Dirac equations Feynman considered their associated Green's functions, classes of solutions to the inhomogeneous differential equations. These Green's functions, generally referred to as kernels and written in the form $K(2,1)$, do not describe particular paths taken by a particle through space–time, but rather characterize the entirety of possible paths available to a particle on its journey between space–time points 1 and 2. These kernels thus correspond to the probability amplitudes for given subatomic events. Given Feynman's interpretation of positrons, point 1 need not occur earlier than point 2. In a modular fashion, probability amplitudes of fundamental processes can be used to subsequently calculate the amplitudes of more complex quantum events.

Finally, and perhaps most famously, Feynman's new space–time approach involved the development of a diagrammatic method for computing the contributions of possible interactions of subatomic events. ''Feynman diagrams'', as they came to be known, were developed after the Second World War, which Feynman spent working at Los Alamos on the Manhattan Project.[6] These diagrams arose out of Feynman's attempts to understand the Dirac equation, the quantum wave equation for relativistic particles, and his efforts to construct a physical ''picture'' capable of accompanying the ''terrifying'' power of mathematics.[7] By developing a method in which these simple diagrams could be used to perform complicated quantum electrodynamic calculations, Feynman diagrams would come to be an integral component of the mathematical, as well as conceptual, apparatus of Feynman's ''new approach'' to QED.

Before long, Freeman Dyson (born 1923) demonstrated that Feynman's diagrammatic approach could be shown to be functionally equivalent to field-theoretical approaches to QED developed by Julian Schwinger (1918–1994) and Sin-Itiro (Shinichiro) Tomonaga (1908–1979), with whom Feynman would share the 1965 Nobel Prize in Physics.[8] In the context of Schwinger and Tomonaga's rather mathematically-challenging methodology, Dyson described the primary advantage of Feynman diagrams as their ability to greatly facilitate calculations, although there is of course also much to be said regarding the heuristic advantages afforded by being able to generate simple pictures of complicated theoretical interactions. Understood as a graphical means of computing perturbation terms for a given event, Dyson's formalized interpretation of Feynman's diagrams (or ''graphs'', as he called them) was published in his ''The Radiation Theories of Schwinger, Tomonaga, and Feynman'' in the *Physical Review* in February 1949.[9] Feynman's own articles describing his ''new approach'' to QED, which included his re-interpretation of positrons and presentation of Feynman diagrams were submitted to the *Physical Review* in April and May of the same year, and published in September. They were published as ''The Theory of Positrons'' and ''Space–Time Approach to Quantum Electrodynamics'', respectively.[10]

In the summer of 1949, Feynman traveled to the University of Michigan in Ann Arbor to lecture at its annual Summer Symposium in Physics, a venue for students and professors alike commonly referred to as the ''Summer School''. Here, Feynman was tasked with presenting his ''new approach'' to QED which he had recently described in his articles submitted to the *Physical Review*. While Feynman arrived at Ann Arbor as a respected member of the physics community, he nevertheless remained a relative methodological outsider; his version of QED was founded upon non-standard mathematical techniques, contained novel physical reinterpretations of fundamental particles, and involved a strange, new diagrammatic method of computing results. Feynman was not truly alone, as his methods had been adopted by Dyson and a small number of other individuals, such as Robert Karplus and Norman Kroll, and an increasing number of physicists were learning about them through circulated preprints of Feynman's articles.[11] However, Feynman's approach was still relatively unknown, and it was still far from certain whether or not it would be ultimately adopted over more conventional field-theoretic methods. Yet, Feynman had faith in his theory, having checked his results against Schwinger's, and was eager to describe his

4 Feynman (2005).

5 For a detailed analysis of Feynman's ''great struggle'' with the Dirac equation, see Wüthrich (2010, Chap. 4).

6 For more on Feynman's war work, including insight into the roots of his modular, pictorial approach to QED, see Galison (1998).

7 ''The power of mathematics is terrifying—and too many physicists finding they have correct equations without understanding them have been so terrified they give up trying to understand them. I want to go back & try to understand them.'' Feynman to his good friend, Theodore Welton, CIT, 3.9.

8 Dyson (1949).

9 Dyson (1949) Dyson's use of the term ''graphs'', as opposed to ''diagrams'', is not merely a semantic decision but a conceptual one as well. Dyson approached Feynman diagrams as mathematical entities, not pictorial representations of subatomic interactions, an approach which contrasts to Feynman's use of his own diagrams which he conceived of both mathematically and conceptually. Kaiser has discussed the divergent interpretations of Feynman and Dyson regarding how Feynman diagrams should be used and understood, and refers to this difference of opinions as the ''Feynman–Dyson split''. Kaiser (2005, pp. 175–195).

10 Feynman (1949a, 1949b)

11 Karplus and Kroll used Feynman diagrams and ''the methods of Dyson'' to calculate the fourth order radiative correction to the magnetic moment of the electron. Their final work was submitted to the *Physical Review* in October 1949. Karplus & Kroll (1950). On the subject of preprints, as Kaiser has argued, reading preprints of Feynman's 1949 papers would by no means ensure that they were understood. In most cases personal interaction was necessary for understanding how to use and conceive of Feynman's diagrams. Kaiser (2005, Chap. 2–4).