

Appendix A

Diagrammatic Induction

It might seem as though one of the limitations of diagrammatic proofs is that they can only express specific statements, not general ones. If one wants to prove that the sum of all the angles in a triangle is 180° , it does not suffice to draw one triangle and to confirm (approximately) the statement. So how can one prove or even express a general statement using a diagram?

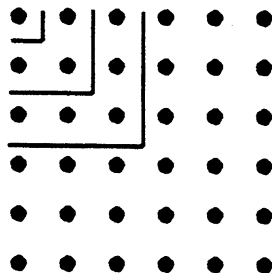
One possibility is by *inductive* proof, much in the same way that inductive proofs are carried out using mathematical formulae. An inductive proof does not need the special features of mathematical or logical formulae and can therefore be performed using other types of symbols as well. In fact, it is even not obvious how one should distinguish mathematical or logical formulae from other types of symbols such as diagrams (see, e. g., Goodman 1968, chapter IV, section 10).

In logic and mathematics one can, for example, prove by induction that a statement is generally true when it has been explicitly verified only for a finite number of special cases. This is possible by establishing a prescription of how all the special cases, one after the other, can be constructed, such that at each stage of the construction the truth of the statement is preserved. If such a prescription is available, the same inductive proof procedure should, therefore, be possible for any kind of symbol, including symbols that one calls diagrams, graphs or drawings. For example, the statement that the sum of the odd numbers up to $2n - 1$ equals n^2 can be proved by induction using either mathematical formulae *or* diagrams. Brown (1996, p. 253) also discusses this example; note, however, that he does *not* consider that the variant of the proof using diagrams is a proof by induction.

The standard proof using mathematical formulae is first to verify the statement for the first $n = 1$:

$$\sum_j^1 2j - 1 = 1 = 1^2. \quad (\text{A.1})$$

Fig. A.1 Diagram used to prove that the sum of odd numbers up to $2n - 1$ equals n^2 (Brown 1996, p. 251)



Next, one expresses the general sum up to $2n - 1$ in terms of the sum with one term less, that is up to $2(n - 1) - 1$:

$$\sum_j^n 2j - 1 = \sum_j^{n-1} (2j - 1) + 2n - 1. \quad (\text{A.2})$$

Assuming that the statement holds for the sum with one term less, one obtains

$$(n - 1)^2 + 2n - 1 = n^2 - 2n + 1 + 2n - 1 = n^2. \quad (\text{A.3})$$

Thus one has proved that if the statement holds for a sum up to a certain n , it also holds for the sum with one more term. Since the statement was verified for the lowest possible n , it holds for any n .

Therefore, proof by induction essentially hinges on one being able to construct one member of the class of objects about which one wants to derive a statement out of the previous member, relative to a certain ordering of the members in the class. Yet this can also be done using a *graphical* representation of the members of the class, in our case the odd numbers up to $2n - 1$. One can represent the sequence of odd numbers as sectors in a quadratic array of dots containing n^2 dots (see Fig. A.1). Then one can verify the statement $\sum_j^n 2j - 1 = n^2$ for the special case $n = 1$: one dot is the same as a quadratic array made up of one dot. The next member of the class is obtained by adding an L-shaped segment to the previous member in the lower right-hand side of the diagram, since the L-shaped segment contains an odd number of dots. Adding an L-shaped segment to a square results again in a square, the side of which contains one more dot than the original square. Therefore, if the statement is true for the previous member, it is true for the next member. Since any member of the class can be constructed by adding L-shaped segments, the statement is proved in its full generality.

Appendix B

Synopsis of Manuscripts and Principal Publications

On the following page, I give an overview of the notes and the publications by Feynman as well as the publications by Freeman J. Dyson, Hans Euler and the Japanese physicists working around Sin-Itiro Tomonaga that I discuss in my dissertation. I also include some of the publications by Julian Schwinger and Ernst C. G. Stueckelberg that might be of interest as regards the chronology of the development of Feynman diagrams. For the published work, I give the date of publication; for Feynman's notes, I give the approximate dates that seem most plausible to me on the basis of my reconstruction of the developments.

Manuscripts by Feynman	Publications by Feynman	Publications by others
	1941 Wheeler and Feynman (conference presentation, see 'Minutes of the ...' 1941)	1934 Stueckelberg 1936 Euler 1938 Stueckelberg 1941 Stueckelberg
	1942 PhD thesis (Feynman 2005)	
	1945 Wheeler and Feynman	1946 Tomonaga
ca. 1946	<i>Dirac Equation b, Harmonic Oscillators b</i>	
1946/47	Exchange of letters between Feynman and Theodore Welton (<i>Dirac Equation a</i>)	
ca. 1947	<i>Space-time approach to quantum electrodynamics, Dirac Equation h</i>	
ca. 1948	<i>Advanced Quantum Mechanics (at Cornell), Theory of Positrons ...</i>	1948 Schwinger 1948a (Feb.), Schwinger 1948b (Nov.), RadReactI, RadReactII
early 1950s	<i>Helium</i>	1949 RadReactIIa, RadReactIIb, RadTh (Feb.), SM (June)
	1948 RMP48 (April), CutOffCI (Oct.), CutOffQ (Nov.)	
	1949 Wheeler and Feynman 1949 (July), ThPos (Sept.), STQED (Sept.)	
	1951 Feynman	

References

Abbreviations

RMP48	R. P. Feynman (1948). ‘Space-Time Approach to Non-Relativistic Quantum Mechanics’. In: <i>Reviews of Modern Physics</i> 20.2 (Apr. 1948), pp. 367–387.
ThPos	R. P. Feynman (1949). ‘The Theory of Positrons’. In: <i>Physical Review</i> 76.6 (Sept. 1949), pp. 749–759.
STQED	R. P. Feynman (1949). ‘Space-Time Approach to Quantum Electrodynamics’. In: <i>Physical Review</i> 76.6 (Sept. 1949), pp. 769–789.
RadTh	F. J. Dyson (1949). ‘The Radiation Theories of Tomonaga, Schwinger, and Feynman’. In: <i>Physical Review</i> 75.3 (Feb. 1949), pp. 486–502.
CutOffCl	R. P. Feynman (1948). ‘A Relativistic Cut-Off for Classical Electrodynamics’. In: <i>Physical Review</i> 74.8 (Oct. 1948), pp. 939–946.
CutOffQ	R. P. Feynman (1948). ‘Relativistic Cut-Off for Quantum Electrodynamics’. In: <i>Physical Review</i> 74.10 (Nov. 1948), pp. 1430–1438.
SM	F. J. Dyson (1949). ‘The S Matrix in Quantum Electrodynamics’. In: <i>Physical Review</i> 75.11 (June 1949), pp. 1736–1755.
RadReacI	Z. Koba and S.-I. Tomonaga (1948). ‘On Radiation Reactions in Collision Processes. I.’ In: <i>Progress of Theoretical Physics</i> 3.3, pp. 290–303.
RadReacII	Z. Koba and G. Takeda (1948). ‘Radiation Reaction in Collision Process, II’. In: <i>Progress of Theoretical Physics</i> 3.4, pp. 407–421.
RadReacIIIa	Z. Koba and G. Takeda (1949). ‘Radiation Reaction in Collision Process III1. First Radiative Correction for an Arbitrary Process Including Electrons, Positrons, and Light Quanta’. In: <i>Progress of Theoretical Physics</i> 4.1, pp. 60–70.
RadReacIIIb	Z. Koba and G. Takeda (1949). ‘Radiation Reaction in Collision Process III2. First Radiative Correction for an Arbitrary Process Including Electrons, Positrons, and Light Quanta’. In: <i>Progress of Theoretical Physics</i> 4.2, pp. 130–141.

Cross-References

The bibliography partially functions as an index: At the end of each entry the pages on which the item is cited are indicated by the phrase “See p./pp. ...”.

Classification of the Material from the Feynman Collection Held by the Caltech Archives

The Papers of Richard Phillips Feynman held by the Caltech (California Institute of Technology) Archives have been filed into labelled folders and boxes (91 in total). A finding aid is available at the Archives and online.¹ The Feynman Collection was processed by Charlotte E. Erwin, Carol Finerman and David A. Valone and completed on 1 July 1993. The finding aid was updated in September 2002. The Archives kindly permitted me to take digital photographs of parts of those folders which contained possibly relevant material for my area of investigation. Thus, from some of the folders I selected several series of folios, which I labelled, for the purposes of my research, *a*, *b*, *c*, etc., in the order that they appear in the folder. The particular folios in a series are referred to as the first, second, third, etc., folio in the series in the order that they appear in it, irrespective of any page-numbering system that Feynman may have applied to his notes. Note that under normal circumstances the folios made available to researchers are photocopies of Feynman’s original papers. Therefore, Feynman’s notes on the verso of a piece of paper appear as separate folios in the Archives. I have used the title given by the archivists to refer to a particular folder in a box, the numbers of which are given in the references below. For example, “*Dirac Equation a*, folio 11” refers to the 11th folio in series *a* from Folder 2 in Box 11, which was given the title “Dirac Equation” by the archivists. If no series label is given, then I have selected only one series of folios from the relevant folder (but the whole folder is not necessarily made up of only this one series).

I was able to date only one of the folios precisely (*Dirac Equation a*, folio 1, see page 80). Nevertheless, I indicate for each series of folios the approximate dates that seem most plausible to me on the basis of my reconstruction of the developments.

For internal use only, I have stored my selection of 588 folios in jpeg format in the digital library of the Institute of Philosophy of the University of Bern. On request, and with the agreement of the Caltech Archives, the Institute of Philosophy will grant interested researchers access to this material.

¹ The online finding aid is provided by the Online Archive of California, and is available at <http://www.oac.cdlib.org/findaid/ark:/13030/kt5n39p6k0>, last visited 12 July 2010.

References to the Material from the Feynman Collection

- Advanced Quantum Mechanics (at Cornell)*. (ca. 1948). Series of selected folios from Box 7, Folder 4. See pp. [xi](#), [31](#), and [194](#)
- Dirac Equation a*. (1946/47). First series of selected folios from Box 11, Folder 2. See pp. [xiii](#), [xiv](#), [77](#), [78](#), [79](#), [80](#)
- Dirac Equation b*. (Ca. 1946). Second series of selected folios from Box 11, Folder 2. See pp. [xiii](#), [xvi](#), [67](#), [69](#), [75](#)
- Dirac Equation h*. (Ca. 1947). Eighth series of selected folios from Box 11, Folder 2. See pp. [xv](#), [xvii](#), [107](#), [108](#)
- Theory of Positrons; Self-Energy in an Atom; Radiation Scattering; Spreading Dirac Packet*. (Ca. 1948). Series of selected folios from Box 13, Folder 1. See pp. [xv](#), [128](#), and [129](#)
- Harmonic Oscillators b*. (Ca. 1946). Second series of selected folios from Box 11, Folder 5. See p. [194](#)
- Helium*. (Early 1950s). Series of selected folios from Box 11, Folder 6. See pp. [xiii](#), [59](#), and [194](#)
- Space-Time Approach to Quantum Electrodynamics*. (Ca. 1947). Series of selected folios from Box 12, Folder 9. See pp. [xvi](#) and [181](#)

Other References

- Baeyer, H. C. von (1999). 'Nota Bene'. In: *The Sciences* (January/February 1999). New York, NY: The New York Academy of Sciences, pp. 12–15. See pp. [5](#) and [6](#)
- Bethe, H. A. (1947). 'The Electromagnetic Shift of Energy Levels'. In: *Physical Review* 72.4 (Aug. 1947), pp. 339–341. See p. [34](#)
- Bethe, H. A. and S. S. Schweber (1955). *Mesons and Fields*. New York, NY: Row, Peterson. See p. [21](#)
- Bopp, F. (1940). 'Eine lineare Theorie des Elektrons'. In: *Annalen der Physik* 38, pp. 345–384. See pp. [139](#)
- Bopp, F. (1942). 'Lineare Theorie des Elektrons. II'. In: *Annalen der Physik* 42, pp. 573–608. See pp. [139](#)
- Breit, G. (1928). 'An Interpretation of Dirac's Theory of the Electron'. In: *Proceedings of the National Academy of Sciences of the United States of America* 14.7, pp. 553–559. See pp. [65](#) and [178](#)
- Breit, G. and J. A. Wheeler (1934). 'Collision of Two Light Quanta'. In: *Physical Review* 46.12 (Dec. 1934), pp. 1087–1091. See p. [25](#)
- Brown, H. R. and R. Harrè, eds. (1988). *Philosophical Foundations of Quantum Field Theory*. Oxford: Clarendon Press.
- Brown, J. R. (1996). 'Illustration and Inference'. In: *Picturing Knowledge: Historical and Philosophical Problems Concerning the Use of Art in Science*. Ed. by B. Baigrie. Toronto, ON: University of Toronto Press. Chap. 8, pp. 250–268. See pp. [xvii](#), [5](#), [191](#), and [192](#)
- Brown, L. M., ed. (1993). *Renormalization. From Lorentz to Landau (and Beyond)*. New York, NY: Springer. See p. [12](#)
- Carson, C. (1996a). 'The Peculiar Notion of Exchange Forces—I: Origins in Quantum Mechanics, 1926–1928'. In: *Studies In History and Philosophy of Science Part B: Studies In History and Philosophy of Modern Physics* 27.1 (Mar. 1996), pp. 23–45. See p. [134](#)
- Carson, C. (1996b). 'The Peculiar Notion of Exchange Forces—II: From Nuclear Forces to QED, 1929–1950'. In: *Studies In History and Philosophy of Science Part B: Studies In History and Philosophy of Modern Physics* 27.2 (June 1996), pp. 99–131. See p. [134](#)
- Cartwright, N. (1983). *How the Laws of Physics Lie*. Oxford: Clarendon Press. See pp. [65](#) and [178](#)
- Compton, A. H. (1923). 'A Quantum Theory of the Scattering of X-rays by Light Elements'. In: *Physical Review* 21.5 (May 1923), pp. 483–502. See pp. [xi](#), [30](#), and [32](#)
- Dancoff, S. M. (1939). 'On Radiative Corrections for Electron Scattering'. In: *Physical Review* 55.10 (May 1939), pp. 959–963. See pp. [12](#) and [13](#)
- Devoto, A. and D. Duke (1984). 'Table of integrals and formulae for Feynman diagram calculations'. In: *La Rivista del Nuovo Cimento (1978–1999)* 7.6 (June 1984), pp. 1–39. See p. [29](#)
- Dirac, P. A. M. (1930). 'A Theory of Electrons and Protons'. In: *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character* 126.801, pp. 360–365. See p. [180](#)
- Dirac, P. A. M. (1933). 'The Lagrangian in Quantum Mechanics'. In: *Physikalische Zeitschrift der Sowjetunion* 3.1, pp. 64–72. See p. [53](#)

- Dirac, P. A. M. (1935). *The Principles of Quantum Mechanics* by P. A. M. Dirac. 2nd ed. Oxford: Clarendon Press. See pp. [52](#), [53](#), [54](#), [65](#), [93](#), [95](#), and [180](#)
- Dirac, P. A. M. (1938). 'Classical Theory of Radiating Electrons'. In: *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences* 167.929 (Aug. 1938), pp. 148–169. See p. [51](#)
- Dirac, P. A. M. (1946). 'Elementary Particles and their Interactions'. In: *The Collected Works of P. A. M. Dirac, 1924–1948*. Ed. by R. H. Dalitz. Paper given at Princeton University Bicentennial. Cambridge: Cambridge University Press. See p. [93](#)
- Dresden, M. (1993). 'Renormalization in Historical Perspective—The First Stage'. In: *Renormalization. From Lorentz to Landau (and Beyond)*. Ed. by L. M. Brown. New York, NY: Springer. See pp. [11](#) and [21](#)
- Dyson, F. J. (1949). 'The Radiation Theories of Tomonaga, Schwinger, and Feynman'. In: *Physical Review* 75.3 (Feb. 1949), pp. 486–502. See pp. [xv](#), [128](#), [143](#), [145](#), [147](#), [148](#), [149](#), [150](#), [151](#), [154](#), [155](#), [156](#), [157](#)
- Dyson, F. J. (1949). 'The S Matrix in Quantum Electrodynamics'. In: *Physical Review* 75.11 (June 1949), pp. 1736–1755. See pp. [xvi](#), [16](#), [50](#), [166](#), [167](#), [168](#), [169](#), [170](#), [171](#), [172](#), [173](#), [174](#), [175](#), [188](#), and [194](#)
- Dyson, F. J. (1965). 'Tomonaga, Schwinger, and Feynman Awarded Nobel Prize for Physics'. In: *Science*. 3rd ser. 150.3696 (Oct. 1965), pp. 588–589. See pp. [11](#) and [188](#)
- Dyson, F. J. (2006). *Advanced Quantum Mechanics: Second Edition*. URL: <http://arxiv.org/abs/quant-ph/0608140v1>. See pp. [8](#), [9](#), and [156](#)
- Euler, H. (1936). 'Über die Streuung von Licht an Licht nach der Diracschen Theorie'. In: *Annalen der Physik* 418.5, pp. 398–448. See pp. [xi](#), [19](#), [23](#), [24](#), [25](#), [26](#), [27](#), [28](#), [32](#), [37](#), [172](#), and [194](#)
- Euler, H. and B. Kockel (1935). 'Über die Streuung von Licht an Licht nach der Diracschen Theorie'. In: *Naturwissenschaften* 23.15 (Apr. 1935), pp. 246–247. See p. [172](#)
- Fermi, E. (1932). 'Quantum Theory of Radiation'. In: *Reviews of Modern Physics* 4.1 (Jan. 1932), pp. 87–132. See pp. [62](#) and [133](#)
- Feynman, R. P. (1948). 'A Relativistic Cut-Off for Classical Electrodynamics'. In: *Physical Review* 74.8 (Oct. 1948), pp. 939–946. See pp. [133](#), [134](#), [139](#), [150](#), [184](#), and [194](#)
- Feynman, R. P. (1948). 'Relativistic Cut-Off for Quantum Electrodynamics'. In: *Physical Review* 74.10 (Nov. 1948), pp. 1430–1438. See pp. [133](#), [134](#), [139](#), [150](#), and [194](#)
- Feynman, R. P. (1948). 'Space-Time Approach to Non-Relativistic Quantum Mechanics'. In: *Reviews of Modern Physics* 20.2 (Apr. 1948), pp. 367–387. See pp. [57](#), [58](#), [60](#), [62](#), [63](#), [64](#), [66](#), [71](#), [75](#), [77](#), [92](#)
- Feynman, R. P. (1949). 'Space-Time Approach to Quantum Electrodynamics'. In: *Physical Review* 76.6 (Sept. 1949), pp. 769–789. See pp. [xv](#), [xvii](#), [11](#), [15](#), [128](#), [130](#), [131](#), [132](#), [133](#), [134](#), [135](#), [136](#), [137](#), [138](#), [139](#)
- Feynman, R. P. (1949). 'The Theory of Positrons'. In: *Physical Review* 76.6 (Sept. 1949), pp. 749–759. See pp. [xv](#), [xvii](#), [96](#), [113](#), [114](#), [115](#), [116](#), [117](#), [118](#), [119](#), [120](#), [121](#), [122](#), [123](#), [124](#), [125](#), [126](#), [127](#), [128](#)
- Feynman, R. P. (1951). 'An Operator Calculus Having Applications in Quantum Electrodynamics'. In: *Physical Review* 84.1 (Oct. 1951), pp. 108–128. See pp. [141](#) and [194](#)
- Feynman, R. P. (1966). 'The Development of the Space-Time View of Quantum Electrodynamics'. In: *Science* 153.3737. Nobel lecture, pp. 699–708. See pp. [6](#), [11](#), [93](#), [95](#), and [180](#)
- Feynman, R. P. (2005). 'The Principle of Least Action in Quantum Mechanics'. In: *Feynman's Thesis: A New Approach to Quantum Theory*. Ed. by L. M. Brown. Singapore: World Scientific Publishing, pp. 1–69. See pp. [51](#), [52](#), [53](#), [54](#), [55](#), [56](#), [57](#), [61](#), [103](#), [104](#), and [194](#)
- Feynman, R. P. and A. R. Hibbs (1965). *Quantum Mechanics and Path Integrals*. New York, NY: McGraw-Hill. See p. [65](#)
- Fokker, A. D. (1929). 'Ein invarianter Variationsatz für die Bewegung mehrerer elektrischer Massenteilchen'. In: *Zeitschrift für Physik* 58, pp. 386–393. See p. [104](#)
- Frenkel, J. (1925). 'Zur Elektrodynamik punktförmiger Elektronen'. In: *Zeitschrift für Physik A Hadrons and Nuclei* 32.1 (Dec. 1925), pp. 518–534. See p. [51](#)
- Frisch, M. (2005). *Inconsistency, Asymmetry, and Non-Locality: A Philosophical Investigation of Classical Electrodynamics*. Oxford: Oxford University Press. See p. [51](#)
- Furry, W. H. (1937). 'A Symmetry Theorem in the Positron Theory'. In: *Physical Review* 51.2 (Jan. 1937), pp. 125–129. See p. [170](#)
- Galison, P. (1983). 'The Discovery of The Muon and the Failed Revolution Against Quantum Electrodynamics'. In: *Centaurus* 26, pp. 262–316. See p. [19](#)

- Galison, P. (1998). 'Feynman's War: Modelling Weapons, Modelling Nature'. In: *Studies In History and Philosophy of Science Part B: Studies In History and Philosophy of Modern Physics* 29.3 (Sept. 1998), pp. 391–434. See pp. 77, 114, and 182
- Giere, R. N. (1996). 'Visual Models and Scientific Judgement'. In: *Picturing Knowledge: Historical and Philosophical Problems Concerning the Use of Art in Science*. Ed. by B. Baigrie. Toronto, ON University of Toronto Press, pp. 267–302. See p. 178
- Gleick, J. (1992). *Genius: The Life and Science of Richard Feynman*. Originally published: New York: Pantheon Books/Vintage Books. See pp. 61 and 144
- Goodman, N. (1968). *Languages of Art: An Approach to a Theory of Symbols*. Indianapolis, IN: Hackett Publishing. See pp. 10, 14, and 191
- Gräßhoff, G., H.-C. Liess and K. Nickelsen (2002). 'Visualisiertes Wissen: Eine Einführung in die Analyse wissenschaftlicher Abbildungen'. Unpublished manuscript. History and Philosophy of Science. University of Bern. See p. 10
- Griffiths, D. (1987). *Introduction to Elementary Particles*. Hoboken, NJ: Wiley. See pp. xi and 3
- Halpern, O. (1933). 'Scattering Processes Produced by Electrons in Negative Energy States'. In: *Physical Review* 44.10 (Nov. 1933), pp. 855–856. See p. 23
- Harré, R. (1988). 'Parsing the Amplitudes'. In: *Philosophical Foundations of Quantum Field Theory*. Ed. by H. R. Brown and R. Harré. Oxford: Clarendon Press, pp. 59–71. See pp. 2 and 9
- Heisenberg, W. (1934). 'Bemerkungen zur Diracschen Theorie des Positrons'. In: *Zeitschrift für Physik A Hadrons and Nuclei* 90.3 (Mar. 1934), pp. 209–231. See p. 26
- Heisenberg, W. (1943). 'Die "beobachtbaren Größen" in der Theorie der Elementarteilchen'. In: *Zeitschrift für Physik A Hadrons and Nuclei* 120.7 (July 1943), pp. 513–538. See p. 166
- Heitler, W. (1944). *Quantum Theory of Radiation*. 2nd ed. London: Oxford University Press. See pp. xi and 32
- Huggett, N. (2000). 'Philosophical Foundations of Quantum Field Theory'. In: *The British Journal for the Philosophy of Science* 51.4, pp. 617–637. See p. 4
- Jacobson, T. and L. S. Schulman (1984). 'Quantum Stochastics: The Passage from a Relativistic to a Non-relativistic Path Integral'. In: *Journal of Physics A: Mathematical and General* 17.2, pp. 375–383. See p. 73
- Kaempffer, F. A. (1965). *Concepts in Quantum Mechanics*. New York, NY: Academic. See pp. 3 and 10
- Kaiser, D. (2005). *Drawing Theories Apart: The Dispersion of Feynman Diagrams in Postwar Physics*. Chicago: The University of Chicago Press. See pp. xii, 3, 7, 9, 10, 27, 30, 34, 37, and 40
- Karplus, R. and M. Neuman (1950). 'Non-Linear Interactions Between Electromagnetic Fields'. In: *Physical Review* 80.3 (Nov. 1950), pp. 380–385. See pp. xi and 29
- Kauffman, L. H. and H. P. Noyes (1996). 'Discrete Physics and the Dirac Equation'. In: *Physics Letters A* 218.3–6 (Aug. 1996), pp. 139–146. See p. 106
- Koba, Z. and G. Takeda (1948). 'Radiation Reaction in Collision Process, II'. In: *Progress of Theoretical Physics* 3.4, pp. 407–421. See pp. xii, 19, 23, 33, 35, 36, 42, 49, and 194
- Koba, Z. and G. Takeda (1949a). 'Radiation Reaction in Collision Process III1. First Radiative Correction for an Arbitrary Process Including Electrons, Positrons, and Light Quanta'. In: *Progress of Theoretical Physics* 4.1, pp. 60–70. See pp. xii, 19, 23, 33, 36, 37, 38, 39, 40, 41, 42, 43, 44, 47, 49
- Koba, Z. and G. Takeda (1949b). 'Radiation Reaction in Collision Process III2. First Radiative Correction for an Arbitrary Process Including Electrons, Positrons, and Light Quanta'. In: *Progress of Theoretical Physics* 4.2, pp. 130–141. See pp. xii, 19, 23, 33, 43, 44, 45, 46, 47, 48, 49, and 194
- Koba, Z. and S.-I. Tomonaga (1948). 'On Radiation Reactions in Collision Processes. I'. In: *Progress of Theoretical Physics* 3.3, pp. 290–303. See pp. xii, 19, 23, 33, 34, 35, and 194
- Kuhn, T. S. (1962). *The Structure of Scientific Revolutions*. 1st ed. Vol. 2. International Encyclopedia of Unified Science 2. (2nd ed. 1970). Chicago: University of Chicago Press. See p. 21
- Kusch, P. and H. M. Foley (1948). 'The Magnetic Moment of the Electron'. In: *Physical Review* 74.3 (Aug. 1948), pp. 250–263. See p. 13
- Lacki, J., H. Ruegg and V. Telegdi (1999). *The Road to Stueckelberg's Covariant Perturbation Theory as Illustrated by Successive Treatments of Compton Scattering*. URL: <http://arxiv.org/abs/physics/9903023>. See p. 12
- Lamb, W. E. and R. C. Retherford (1947). 'Fine Structure of the Hydrogen Atom by a Microwave Method'. In: *Physical Review* 72.3 (Aug. 1947), pp. 241–243. See p. 13

- Leutwyler, H. (1986). 'Elektrodynamik und Optik'. Lecture notes, Institute for Theoretical Physics, University of Bern. See p. 51
- 'Minutes of the Cambridge, Massachusetts, Meeting, February 21 and 22, 1941' (1941). In: *Physical Review* 59.8 (Apr. 1941), pp. 682–691. See p. 52
- McManus, H. (1948). 'Classical Electrodynamics without Singularities'. In: *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences* 195.1042, pp. 323–336. See pp. 139
- Mehra, J. (1994). *The Beat of a Different Drum: The Life and Science of Richard Feynman*. New York, NY: Oxford University Press. See p. 11
- Meynell, L. (2008). 'Why Feynman Diagrams Represent'. In: *International Studies in the Philosophy of Science* 22.1, pp. 39–59. See pp. 3, 4, 6, and 13
- Miller, A. I. (1984). *Imagery in Scientific Thought: Creating 20th-Century Physics*. Boston, MA: Birkhäuser. See pp. 6 and 7
- Miller, A. I. (1995). *Early Quantum Electrodynamics: A Sourcebook*. Cambridge: Cambridge University Press. See p. 173
- Mills, R. (1993). 'Tutorial on Infinities in QED'. In: *Renormalization. From Lorentz to Landau (and Beyond)*. Ed. by L. M. Brown. New York: Springer. See p. 50
- Møller, C. (1931). 'Über den Stoß zweier Teilchen unter Berücksichtigung der Retardation der Kräfte'. In: *Zeitschrift für Physik A Hadrons and Nuclei* 70.11 (Nov. 1931), pp. 786–795. See p. 162
- Møller, C. (1932). 'Zur Theorie des Durchgangs schneller Elektronen durch Materie'. In: *Annalen der Physik* 406.5, pp. 531–585. See p. 162
- Nickelsen, K. (2002). 'Entstehung, Inhalt und Funktion wissenschaftlicher Pflanzenbilder des 18. Jahrhunderts'. PhD thesis. University of Bern. See p. 10
- Oppenheimer, J. R. (1950). 'Electron Theory'. In: *Rapports du 8e Conseil de Physique, Solvay*. Reprinted in Schwinger 1958, pp. 145–155, 269–281. See p. 13
- Pais, A. (1986). *Inward Bound: Of Matter and Forces in the Physical World*. New York, NY: Oxford University Press. See pp. 11 and 12
- Pasternack, S. (1938). 'Note on the Fine Structure of Ha and Da'. In: *Physical Review* 54.12 (Dec. 1938), p. 1113. See p. 13
- Pauli, W. (1933). 'Die allgemeinen Prinzipien der Wellenmechanik'. In: *Handbuch der Physik. Vol. 24: Quantentheorie*. Ed. by H. Geiger and K. Scheel. Berlin: Springer, pp. 83–272. See p. 63
- Pauli, W., A. Hermann and K. von Meyenn (1979). *Wissenschaftlicher Briefwechsel mit Bohr, Einstein, Heisenberg, Ua: Scientific Correspondence with Bohr, Einstein, Heisenberg, A. o.* New York, NY: Springer. See p. 13
- Peskin, M. E. and D. V. Schroeder (1995). *An Introduction to Quantum Field Theory*. Boulder, CO: Westview Press. See pp. xi, 2, 5, and 17
- Roqué, X. (1992). 'Møller Scattering: A Neglected Application of Early Quantum Electrodynamics'. In: *Archive for History of Exact Sciences* 44.3 (Sept. 1992), pp. 197–264. See p. 162
- Sakurai, J. J. (1967). *Advanced Quantum Mechanics*. Fifth printing, Jan. 1976. Reading, MA: Addison-Wesley. See pp. 9 and 16
- Sauer, T. (2008). *Remarks on the Origin of Path Integration: Einstein and Feynman*. URL: <http://arxiv.org/abs/0801.1654>. See p. 131
- Schönberg, M. (1946). 'Classical Theory of the Point Electron'. In: *Physical Review* 69.5–6 (Mar. 1946), pp. 211–224. See p. 39
- Schrödinger, E. (1930). 'Über die kräftefreie Bewegung in der relativistischen Quantenmechanik'. In: *Sonderausgabe aus den Sitzungsberichten der Preussischen Akademie der Wissenschaften, Phys. Math. Klasse* 24. Berlin: Verlag der Akademie der Wissenschaften in Kommission bei Walter de Gruyter u. Co. Reprinted in Schrödinger 1984, pp. 357–368, 418–428. See pp. 65, 66, 113
- Schrödinger, E. (1984). *Collected Papers*. Vol. 3. Vienna: Austrian Academy of Sciences. See p. 200
- Schwarzschild, K. (1903). 'Zur Elektrodynamik. I. Zwei Formen des Prinzips der kleinsten Action in der Elektronentheorie'. In: *Königliche Gesellschaft der Wissenschaften zu Göttingen. Mathematisch-physikalische Klasse. Nachrichten*, Issue 3, pp. 126–131. See p. 104
- Schweber, S. S. (1986a). 'Feynman and the Visualization of Space-Time Processes'. In: *Reviews of Modern Physics* 58.2, pp. 449–508. See p. 180

- Schweber, S. S. (1986b). 'Shelter Island, Pocono, and Oldstone: The Emergence of American Quantum Electrodynamics after World War II'. In: *Osiris*. 2nd ser. 2, pp. 265–302. See p. 7
- Schweber, S. S. (1994). *QED and the Men Who Made It: Dyson, Feynman, Schwinger, and Tomonaga*. Princeton: Princeton University Press. See pp. 5, 93, 95, 141, 143, 144, 180, and 186
- Schwinger, J. (1948a). 'On Quantum-Electrodynamics and the Magnetic Moment of the Electron'. In: *Physical Review* 73.4 (Feb. 1948), pp. 416–417. See pp. 13, 149, and 194
- Schwinger, J. (1948b). 'Quantum Electrodynamics. I. A Covariant Formulation'. In: *Physical Review* 74.10 (Nov. 1948), pp. 1439–1461. See pp. 15, 19, 62, 144, and 194
- Schwinger, J. (1958). *Selected Papers on Quantum Electrodynamics*. New York, NY: Dover Publications. See p. 13
- Schwinger, J. (1983). 'Renormalization Theory of Quantum Electrodynamics: An Individual View'. In: *The Birth of Particle Physics*. Ed. by L. Brown and L. Hoddeson. Cambridge: Cambridge University Press, pp. 329–353. See pp. 1, 18, and 173
- Shapere, D. (1984). 'Notes Toward a Post-Positivist Interpretation of Science, Part II'. In: *Reason and the Search for Knowledge*. Ed. by D. Shapere. Dordrecht: Reidel, pp. 352–382. See p. 51
- Shin, S.-J. (1994). *The Logical Status of Diagrams*. Cambridge: Cambridge University Press. See p. 14
- Stueckelberg, E. C. G. (1934). 'Relativistisch invariante Störungstheorie des Diracschen Elektrons I. Teil: Streustrahlung und Bremsstrahlung'. In: *Annalen der Physik* 413.4, pp. 367–389. See pp. 12 and 194
- Stueckelberg, E. C. G. (1938). 'Die Wechselwirkungs Kraefte in der Elektrodynamik und in der Feldtheorie der Kernkraefte (Teil I)'. In: *Helvetica Physica Acta* 11, pp. 225–244. See pp. 12 and 194
- Stueckelberg, E. C. G. (1941). 'Remarque sur la création de paires de particules en théorie de relativité'. In: *Helvetica Physica Acta* 14, pp. 588–594. See pp. 39 and 194
- Tödtli, B. (2004). 'QCD Corrections to the Wilson Coefficients for $b \rightarrow st^+l^-$ in 2HDMs: Photonic Contributions'. MA thesis. University of Bern. See p. 2
- Tetrode, H. (1922). 'Über den Wirkungszusammenhang der Welt. Eine Erweiterung der klassischen Dynamik.' In: *Zeitschrift für Physik* 10, pp. 317–328. See p. 104
- Tomonaga, S.-I. (1946). 'On a Relativistically Invariant Formulation of the Quantum Theory of Wave Fields'. In: *Progress of Theoretical Physics* 1 (Aug. 1946), pp. 27–42. See pp. 144 and 194
- Tomonaga, S.-I. (1973). 'Development of Quantum Electrodynamics'. In: *The Physicist's Conception of Nature*. Ed. by J. Mehra. Copyright 1966 by the Nobel Foundation and Elsevier, Netherlands. D. Reidel. Chap. 19, pp. 404–412. See p. 12
- Wüthrich, A. (2007). 'Book review: "Drawing Theories Apart: The Dispersion of Feynman Diagrams in Postwar Physics. David Kaiser."' In: *Studies in History and Philosophy of Modern Physics* 38.3 (Sept. 2007), pp. 586–589. See p. 10
- Walton, K. (1990). *Mimesis as Make-Believe: On the Foundations of the Representational Arts*. Cambridge, MA: Harvard University Press. See p. 14
- Weinberg, S. (1977). 'The Search for Unity, Notes for a History of Quantum Field Theory'. In: *Daedalus* 106.4, pp. 17–35. See p. 19
- Weinberg, S. (1995). 'Historical Introduction'. In: *The Quantum Theory of Fields*. Cambridge: Cambridge University Press. Chap. 1, pp. 1–48. See pp. 11, 12, 13, and 16
- Weiner, C. (1966a). 'Interview with Dr. Richard Feynman, March 4 to June 28, 1966, Vol. 2'. Niels Bohr Library & Archives, American Institute of Physics, College Park, MD. See pp. 6 and 95
- Weiner, C. (1966b). 'Interview with Dr. Richard Feynman, March 4 to June 28, 1966, Vol. 1'. Niels Bohr Library & Archives, American Institute of Physics, College Park, MD. See pp. 53, 60, and 103
- Weingard, R. (1988). 'Virtual Particles and the Interpretation of Quantum Field Theory'. In: *Philosophical Foundations of Quantum Field Theory*. Ed. by H. R. Brown and R. Harré. Oxford: Clarendon Press, pp. 43–58. See p. 4
- Weisskopf, V. F. (1934). 'Über die Selbstenergie des Elektrons'. In: *Zeitschrift für Physik* 89, pp. 27–39. See p. 16
- Weisskopf, V. F. (1939). 'On the Self-Energy and the Electromagnetic Field of the Electron'. In: *Physical Review* 56.1 (July 1939), pp. 72–85. See pp. 17, 33, 34, and 65
- Weisskopf, V. F. (1983). 'Growing up With Field Theory: The Development of Quantum Electrodynamics'. In: *The Birth of Particle Physics*. Ed. by L. M. Brown and L. Hoddeson. Cambridge: Cambridge University Press. Chap. 3, pp. 56–81. See p. 12

- Welton, T. (2007). 'Memories of Feynman'. In: *Physics Today* 60.2. Written 1983, pp. 46–52. See p. [93](#)
- Wentzel, G. (1943). *Einführung in die Quantentheorie der Wellenfelder*. Wien: Franz Deuticke. See p. [7](#)
- Wheeler, J. A. (1948). '1948 Pocono Conference on Physics'. Notes prepared informally and unofficially by J. A. Wheeler. American Institute of Physics, Niels Bohr Library. See p. [141](#)
- Wheeler, J. A. and R. P. Feynman (1945). 'Interaction with the Absorber as the Mechanism of Radiation'. In: *Reviews of Modern Physics* 17.2–3 (Apr. 1945), pp. 157–181. See pp. [52](#), [103](#), [150](#), and [182](#)
- Wheeler, J. A. and R. P. Feynman (1949). 'Classical Electrodynamics in Terms of Direct Interparticle Action'. In: *Reviews of Modern Physics* 21.3 (July 1949), pp. 425–433. See pp. [xv](#), [xvii](#), [52](#), [103](#)

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