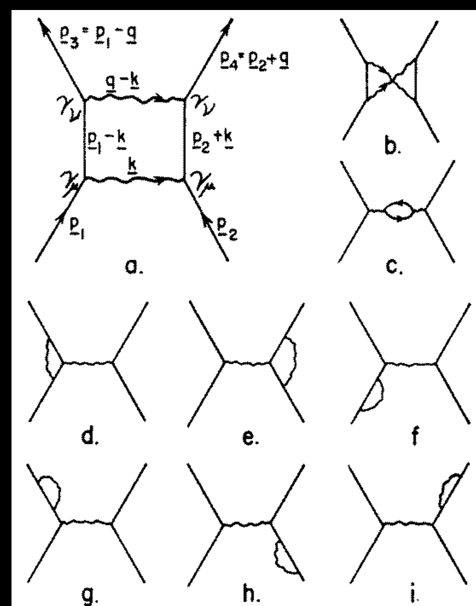
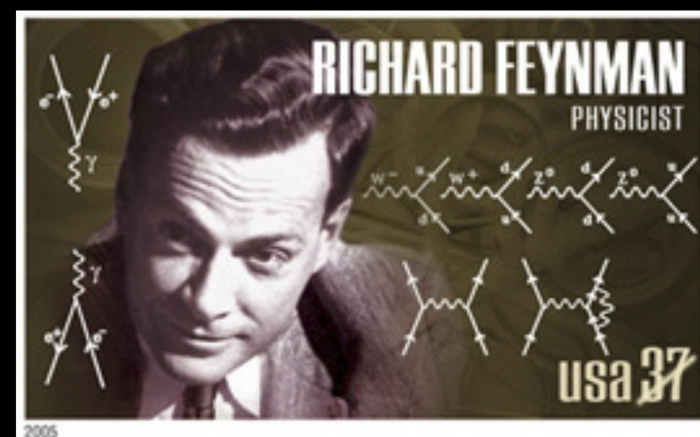
Teaching Feynman's Tools:

The Dispersion of Feynman Diagrams in Postwar Physics





8.225 / STS.042, Physics in the 20th Century
Professor David Kaiser, 18 November 2020

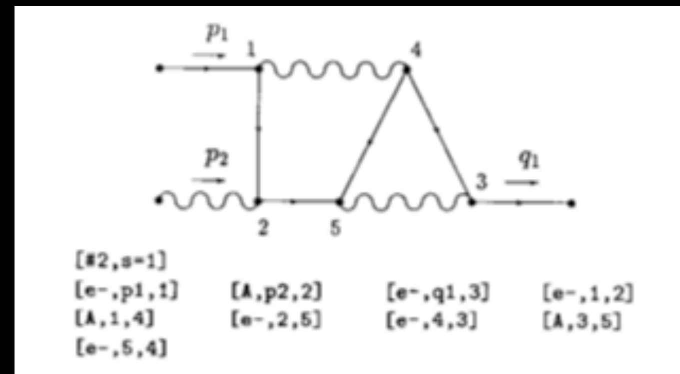
1. Putting New Tools into Circulation

2. Using New Tools toward Different Ends

3. Why Do Some Tools Stick?

Fashioning Feynman Diagrams into Tools

Today Feynman diagrams have become routine: computers can draw and evaluate thousands of them in minutes.



Radiative Corrections to Compton Scattering

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and

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California Institute of Technology, Pasadena, California

(Received August 6, 1951)

Not always that way: evaluating just a handful was a publishable feat in the early 1950s, and the stuff of which dozens of dissertations were made.

Often the diagrams were *adapted* as they were *adopted*.

Despite the diagrams' centrality today, there had been no attention to *how*, by *whom*, or *why* the diagrams were actually used in the 1950s and 1960s.

The Two Meanings of "Dispersion"

Disperse. 1. To distribute from a main source or centre; to put into circulation.
2. To cause to separate in different directions; to put in scattered order.

Questions:

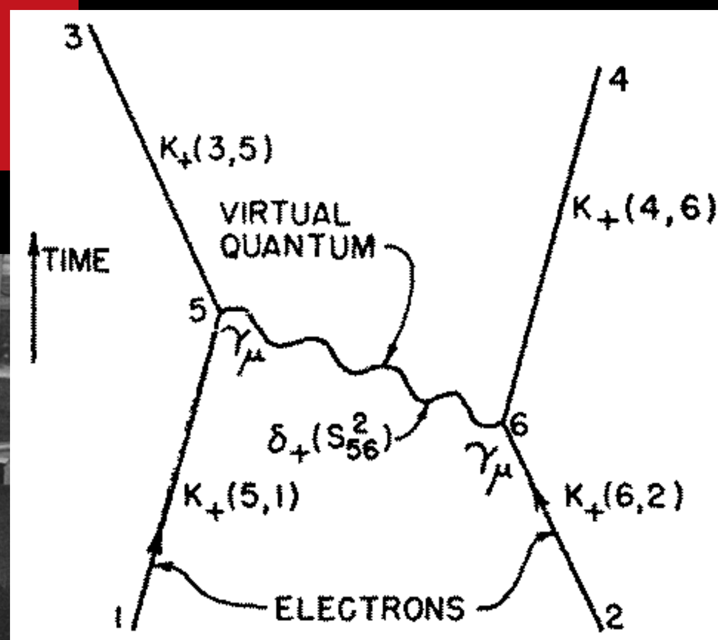
- ***How*** did the diagrams spread so fast?
- For ***what*** were they used during the 1950s and 1960s?
- Given this variety, ***why*** did the diagrams stick?

Feynman and the Introduction of the Diagrams

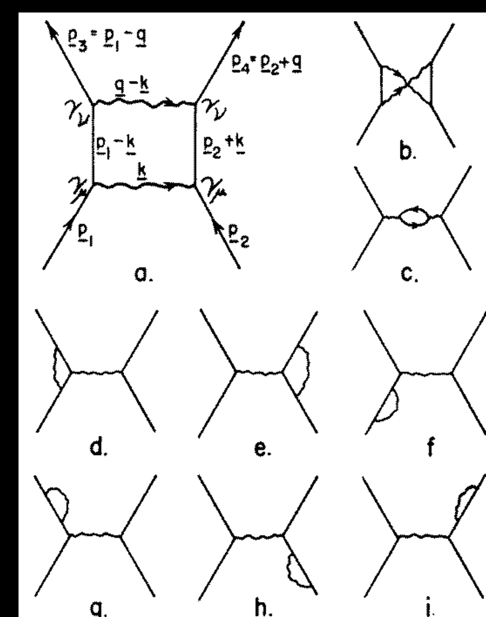
First presented at the 1948 private Pocono conference, as a tool for tackling the infinities of *QED*. The diagrams were a *bookkeeping device* for perturbation theory.

NAS plan for the meeting: "to gather a group consisting of the younger men, who would understand each other's jargon."

$$-ie^2 \iint K_{+a}(3,5)\, K_{+b}(4,6)\, \gamma_{a\mu}\gamma_{b\mu}$$
$$\times\ \delta_+(s_{56}^{\,2})\, K_{+a}(5,1)\, K_{+b}(6,2)\ \ d\tau_5\, d\tau_6$$



Why do electrons repel each other?

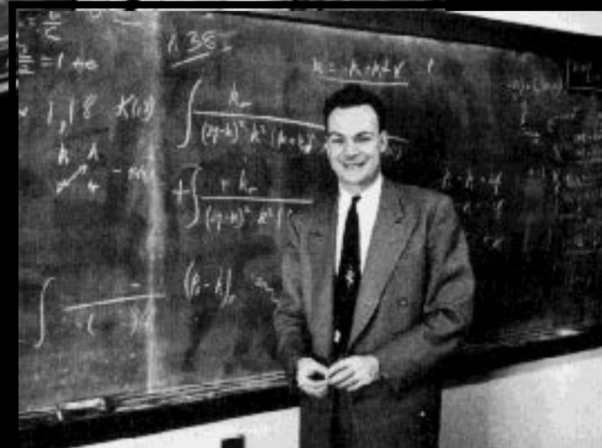


Immediate Reception

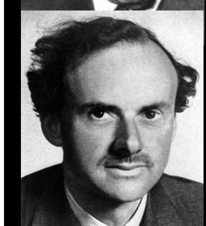
Poor reception at Pocono

Followed Schwinger's ***8-hour lecture***

Feynman was repeatedly interrupted:



Bohr: spacetime pictures violate the uncertainty principle



Dirac: do they obey unitarity?

Teller: what about the exclusion principle for electrons in intermediate states?

In general: what *rules* govern the diagrams' use?

Feynman left the meeting disappointed, even depressed.

Confusion Lingered after Meeting

Bethe to Feynman, summer 1948: "I tried to do your thing, blah blah blah…"

Marshak, December 1948: "We are indebted to Professor Feynman for performing the [diagrammatic] calculation at our request."

Matthews to Pauli et al., February 1950: "We have obtained between us three different answers…"

Pauli to Källén, August 1952: "I am myself not enough of an expert in 'graphs' to be able to check all the details…"

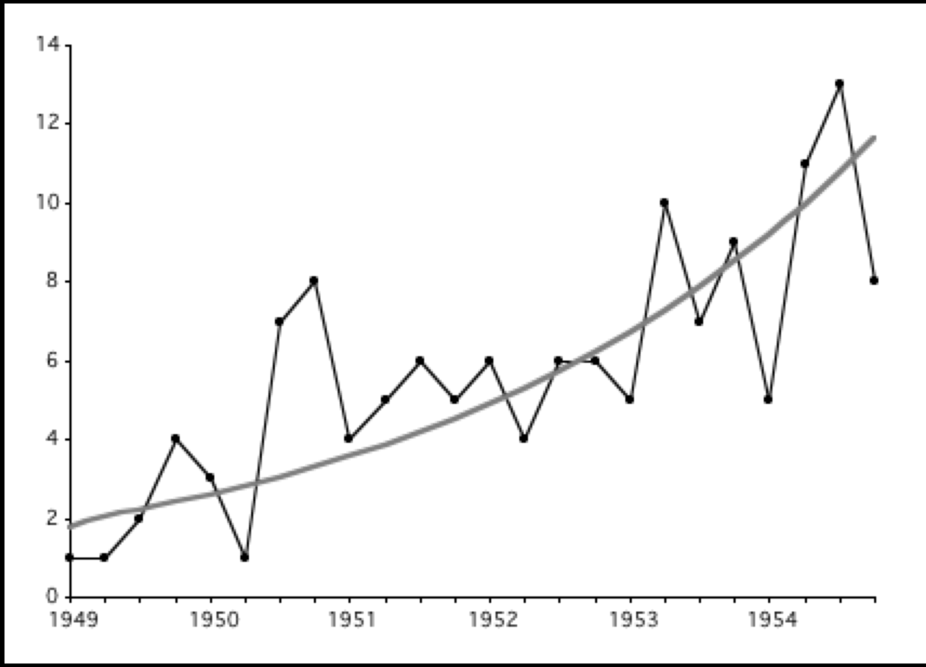
Schiff to Teller, May 1953: My student *does* understand the diagrammatic techniques, and has used them in his dissertation.

The diagrams were not automatic or obvious at first sight.

[and yet…]

Evidence of Dispersion

Number of articles in the *Physical Review* containing Feynman diagrams, 1949-1954



Three shared traits: *young*, *theorists*, and *in contact* with each other

37% of first-time users were *graduate students*

45% of first-time users were *postdocs*

Nearly all the rest were fewer than 7 years past their Ph.D.s

Something *pedagogical* was going on, yet no textbooks published until 1955.

Dyson as Diagrammatic Ambassador

Cornell graduate student, friend of Feynman's.

They drove from Ohio to Albuquerque during summer 1948; FJD attended Schwinger's lectures at Ann Arbor summer school; then he arrived at IAS in fall 1948.

Submitted two articles to *PR* on diagrams in fall 1948.

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	ν - - - → - - - λ	$g_{\nu\lambda}\dfrac{1}{k^2 - i\mu}$	photon propagation function
Internal electron line	—→—	$\dfrac{i\not{p} - m}{p^2 + m^2 - i\mu}$	electron propagation function
Corner	p', p, ν, k	$\gamma^\nu \delta(p - p' - k)$	

Published *before* Feynman's own articles; *cited* more often than Feynman's.

Derived *rules* for diagrams' use; presented "how-to" guide.

Demonstrated *equivalence* of Feynman, Schwinger, and Tomonaga methods.

Argued to Oppenheimer that diagrams are "considerably easier to *use*, *understand*, and *teach*" than other approaches.

Oppenheimer: "Nolo contendere," November 1948, after Bethe's intervention.

New Institution: Postdoctoral Training

Postdocs had been introduced after World War I; still fairly rare for physicists in US after World War II. (Approx. 1 in 6 physics Ph.D.s.) Numbers grew exponentially after the war.

Postdoc positions were *designed* to foster tacit knowledge: meant to supplement "book learning" of the Ph.D. Travel to new places to learn "hands on," and then carry the new skills to another place to begin teaching. All about *circulation*.

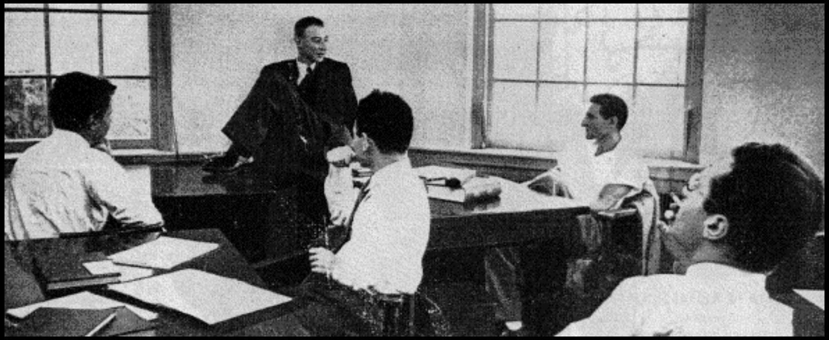
Domestic Training

After World War II, new emphasis on *domestic* training for *theorists*. Most important place: the Institute for Advanced Study (IAS), once Oppenheimer arrived in 1947. Over objections, he increased theorist-postdoc enrollments by 60% in his first year (beginning 1948-49).

Oppenheimer to Pauli, February 1952: The IAS "is not a school in the sense that even the younger people are not listening to lectures or working for doctor's degrees; but it is a school in the sense that everyone who comes learns of parts of physics which are new to him."

IAS: A Factory of Feynman Diagrams

Fall 1948: new IAS building not completed; all theory postdocs shared one big office, just as Dyson arrived.



Postdocs circulated through the IAS "intellectual hotel" for two-year stays; Dyson coordinated group calculations.

Pauli to Pais, May 1949: "What are Dyson and the rest of the 'Feynman-school' working on?"

The postdocs next took jobs elsewhere: *80%* of all the *Physical Review* articles that used Feynman diagrams between 1949-54 arose from these IAS *postdoc cascades*.

Postdoc Cascades

The dispersed postdocs drilled their own graduate students in the diagrams (problem sets, exams, dissertations); other students did not use them.

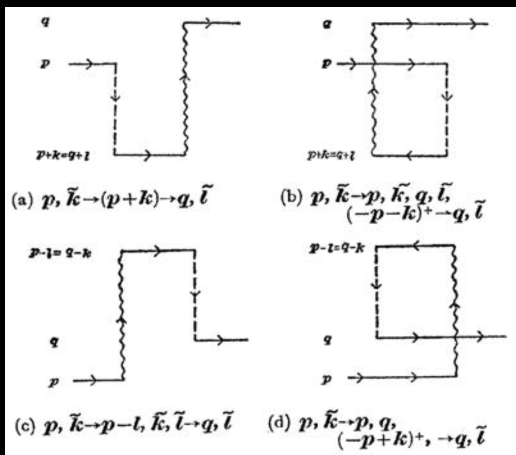
Dyson at IAS, UK, Cornell; *Kroll* to Columbia; *Rohrlich* to Cornell, Princeton, Iowa; *Watson* to Berkeley and Madison; *Karplus* to Harvard and Berkeley…

Gell-Mann to Chicago; *Low* to Urbana; *Brueckner* to Indiana; *Jauch* to Iowa; *Yennie* to Stanford…

disperse: To distribute from a main source of centre; to put into circulation.

International Dispersion

UK: Dyson mentored students in his own former advisor's group at Cambridge, and taught at Birmingham, 1949-1951.



Japan: Tomonaga Sin-itiro's group was already working on similar diagrammatic techniques for perturbative calculations.

The Tokyo group received news and Dyson's preprints from Yukawa Hideki, then at IAS. After *months* of careful study, they began to use Feynman diagrams.

1949 GHQ decree: expand Japanese university system *tenfold*. Members of Tomonaga's group got jobs at Osaka and elsewhere; they worked with physicists throughout Japan.

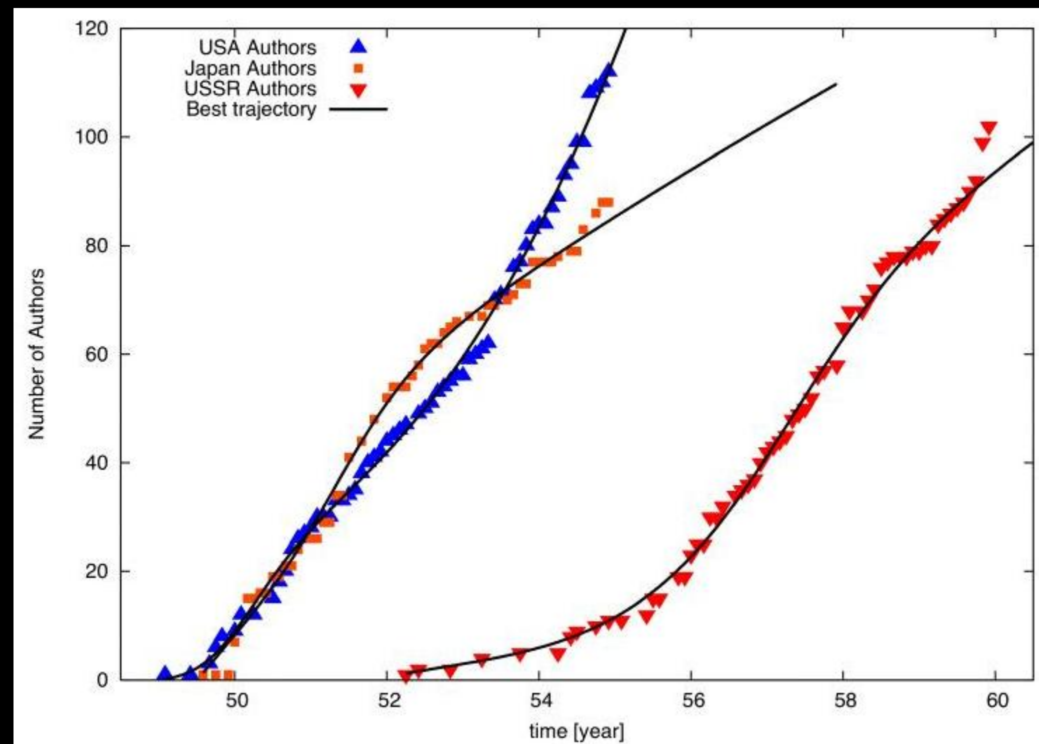
"Natural Experiment": Diagrams in USSR

Cold War: No possibility for personal contact, ca. 1948-1954.

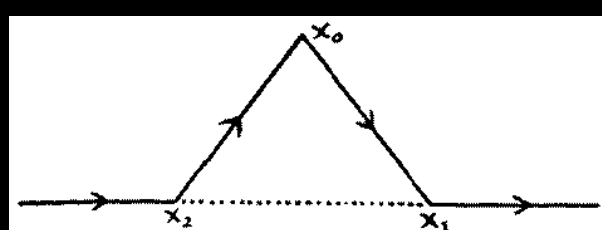
No Feynman diagrams published in Soviet journals until 1952.

Between 1952-54, only 12 Fd papers published in Soviet journals.

Six of these were by the same author! (Top-secret H-bomb assignment: learn to calculate corrections to Compton scattering. Took a full year of studying Feynman's and Dyson's papers.)



All "cookbook" Dyson-rules for perturbative *QED*.



Dyson, 1949

Aleksei Galanin, 1952

Questions?

Question 2: What is it that's dispersing?

disperse: To cause to separate in different directions; to put in scattered order.

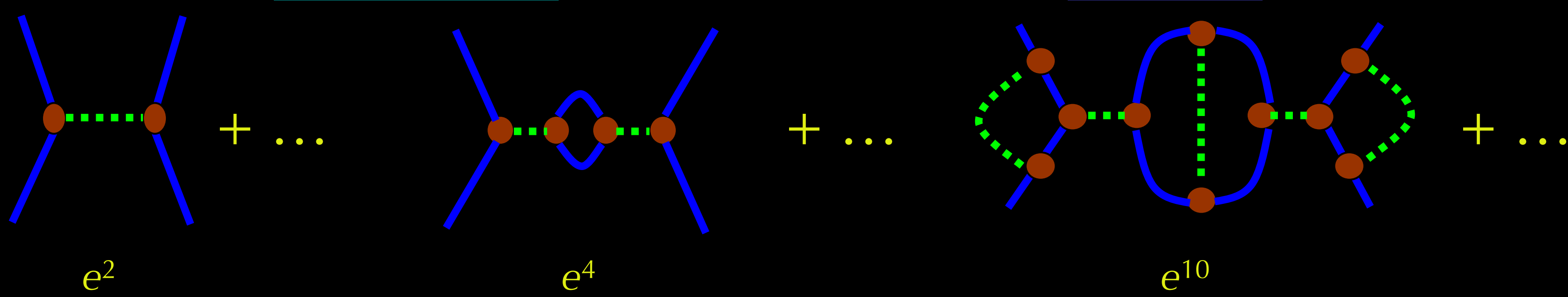
The cascade model misses the rich *heterogeneity* of diagram usage: *pictorial forms*, *relations* with other elements of formalism, and *calculational roles*.

Feynman-Dyson split: "intuitive pictures" versus "merely graphs on paper."

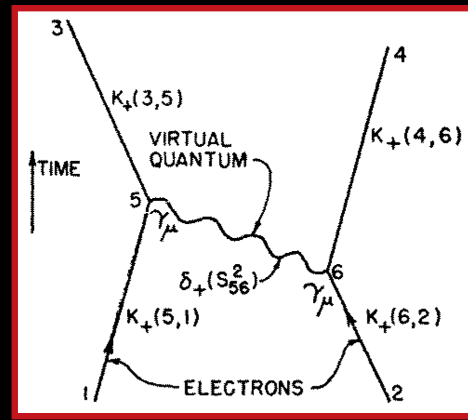
Diagrams most often applied to *strong nuclear force*, for which perturbation theory *broke down*.

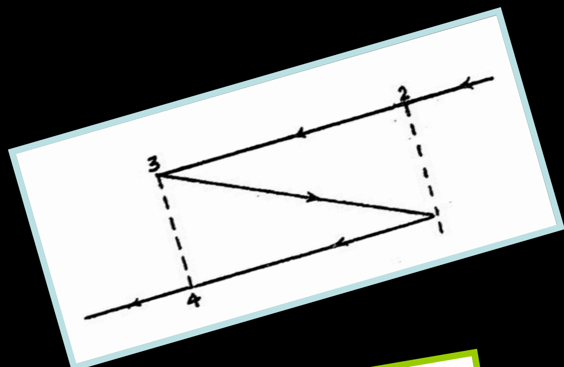
$e^2 \sim 1/137$

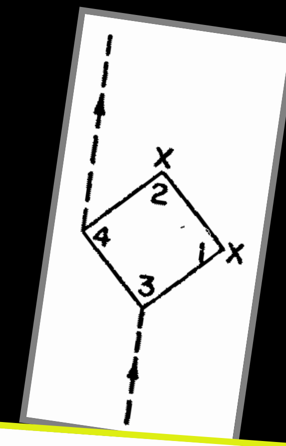
$g^2 \sim 15$

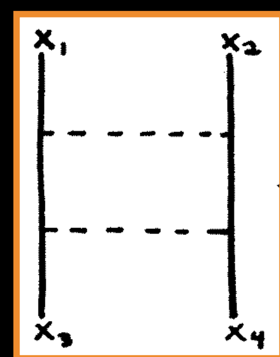


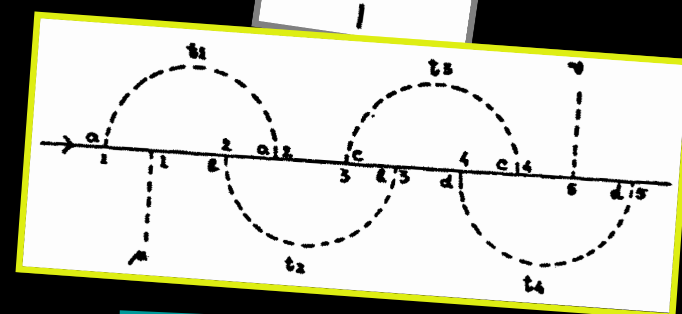
Pictorial Forms

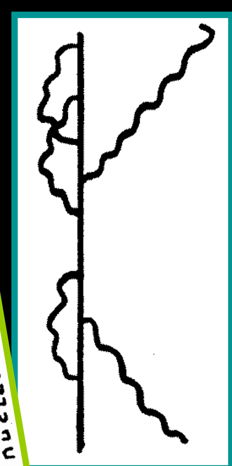


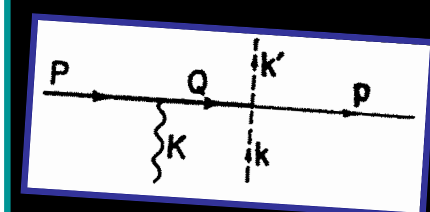


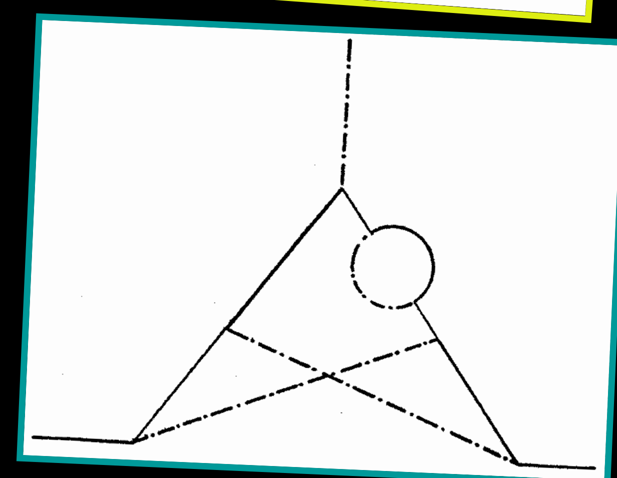








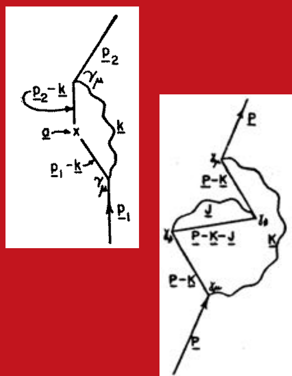




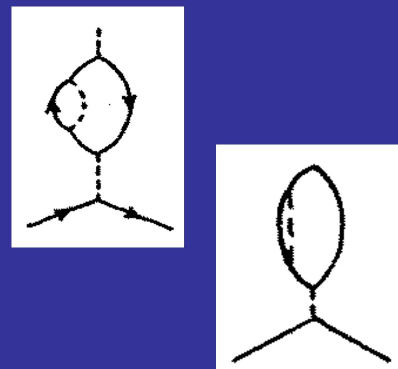
"Feynman diagrams" in the *Physical Review*, 1949-1954

"Family Resemblances": Local Traditions

Cornell

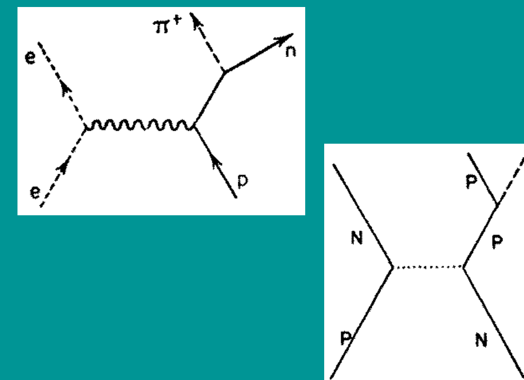


Columbia



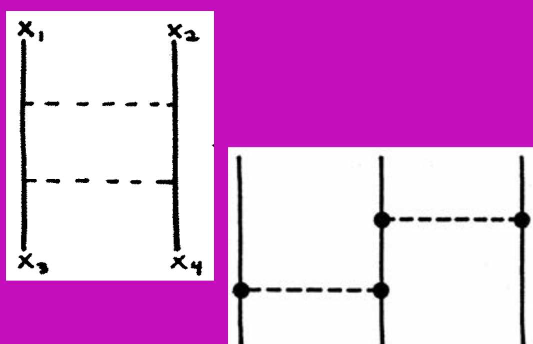
perturbation bookkeepers

Rochester

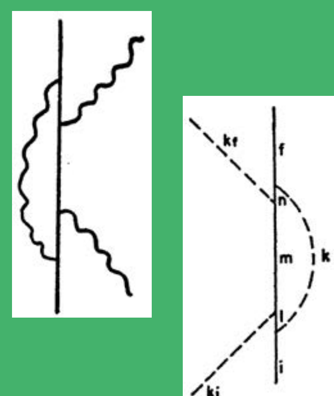


meson scattering

Chicago

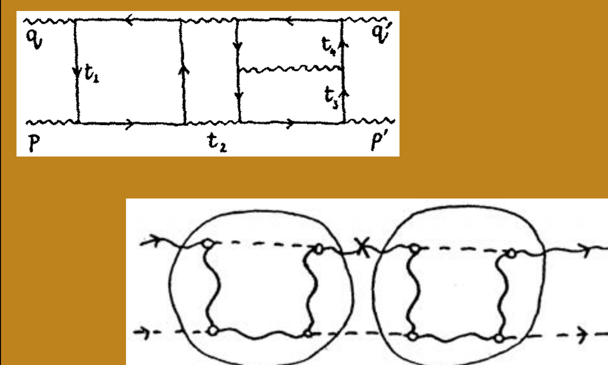


Urbana



bound-state problems

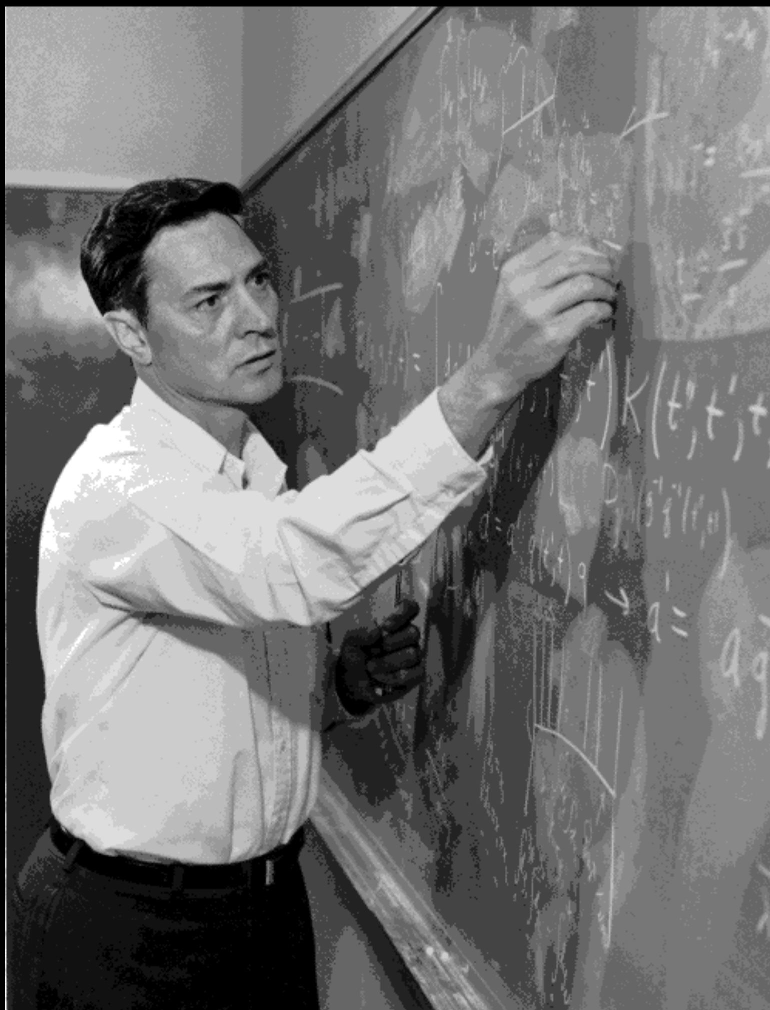
Oxbridge



renormalization

Mentors and students crafted diagrams for different purposes

Geoffrey Chew and "Nuclear Democracy"

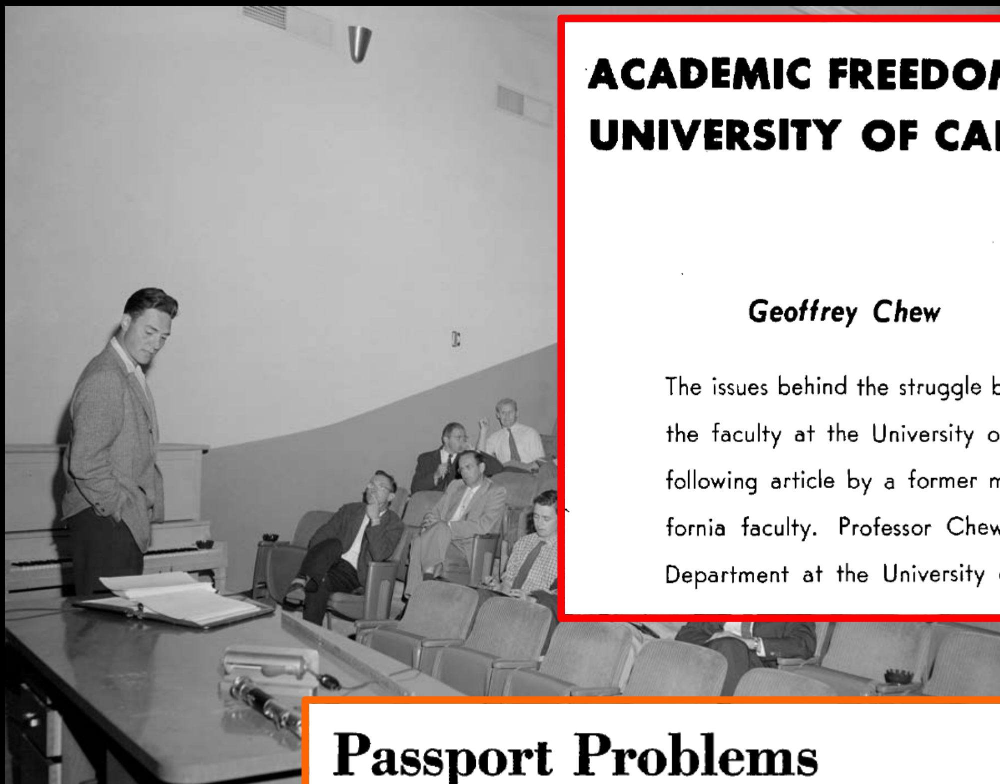


Faced with the breakdown of perturbative methods (large g^2), and the "zoo" of unanticipated particles, Chew introduced radical changes in particle theory.

He declared that QFT is "sterile" for nuclear forces, "destined not to die but just to fade away." (1961)

In its place: "***nuclear democracy***" and the ***bootstrap***. Treat all nuclear particles on an equal footing, rather than dividing them up (à la QFT) into "elementary" versus "composite" sets.

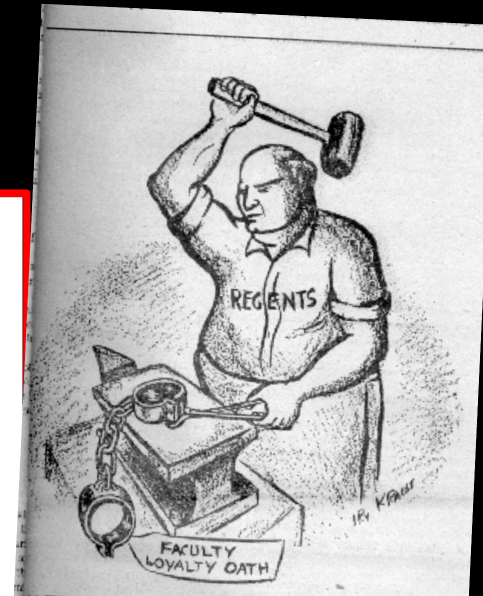
"Nuclear Democracy"



ACADEMIC FREEDOM ON TRIAL AT THE UNIVERSITY OF CALIFORNIA

Geoffrey Chew

The issues behind the struggle between the Board of Regents and the faculty at the University of California are described in the following article by a former member of the University of California faculty. Professor Chew is now teaching in the Physics Department at the University of Illinois.



Daily Cal cartoon, ca. 1949

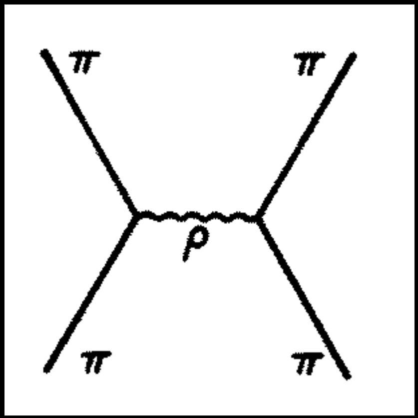
Passport Problems

GEOFFREY CHEW

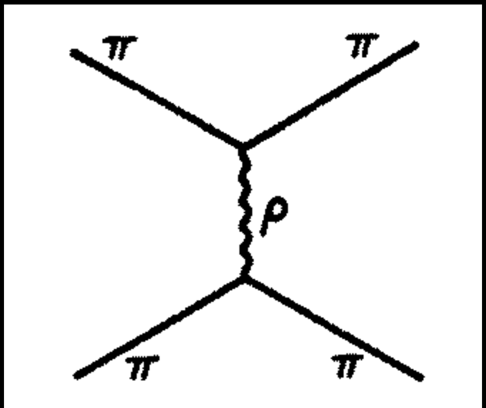
The procedures employed in the issuance of passports and the right to appeal passport refusals was reviewed by the Senate Subcommittee on Constitutional Rights, chaired by Senator Thomas C. Hennings (D. Mo.) at hearings held November 15–16, 1955. Geoffrey F. Chew, Federation of American Scientists Passport Committee Chairman, and physicist from the University of Illinois, testified regarding the cases of five scientists and presented the recommendations of the FAS Passport Committee. Mr. Chew's testimony is printed below and is followed by a summary of the statement made by Professor Linus Pauling.

Same language as in his Senate testimony: no particles should enjoy "special status"; all should be treated as "equal partners under the law."

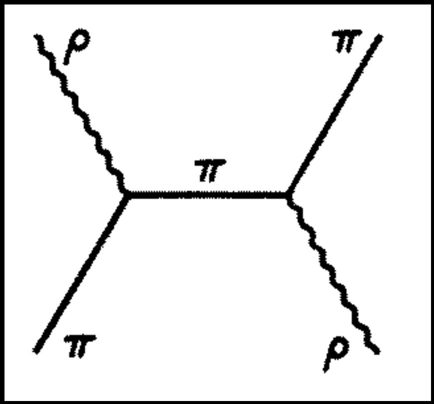
Diagrammatic Democracy



ρ exchanged as ***force-carrying*** particle.



ρ produced as bound-state ***composite***, which then decays into two pions.

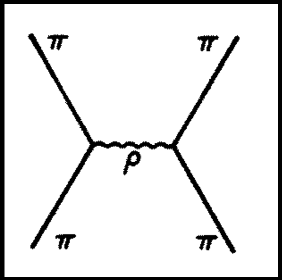


ρ as "***elementary***" particle, scattering with other particles.

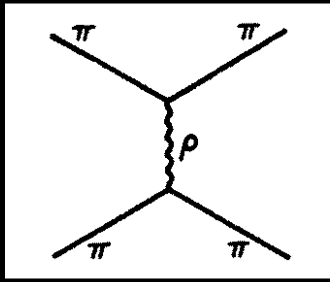
Chew: if the ***diagrams*** make no distinction between "***force-carrying***," "***composite***," and "***elementary***" particles, why should the equations? He sought to ***extract*** Feynman diagrams from QFT and build a new diagram-based theory that would ***replace*** QFT.

The Bootstrap

Chew and his students pressed further: What if every nuclear particle "pulled itself up by its own bootstraps," generating the ***forces*** that would lead to its own ***creation***?



Step 1: A ρ produces an ***attractive force*** between two pions, causing them to approach each other: $F_{\text{force}}(m_\rho, g)$.



Step 2: Upon colliding, the two pions produce a new ***composite*** particle, the ρ: $F_{\text{res}}(m_\rho, g)$.

Two equations for two unknowns! Solve for self-consistent parameters.

Theory	***Experiment***
$m_\rho = 750$ MeV	$m_\rho = 740$ MeV
$g^2 = 13$	$g^2 = 11$

Questions?

Question 3: Why Did the Diagrams Stick?

Within *perturbation theory*, the diagrams' advantage was obvious.

Dyson: "The calculation I did for Hans … took me several months of work and several hundred sheets of paper. Dick could get the same answer, calculating on the blackboard, in half an hour."

Schwinger: "Feynman diagrams brought computation to the masses."

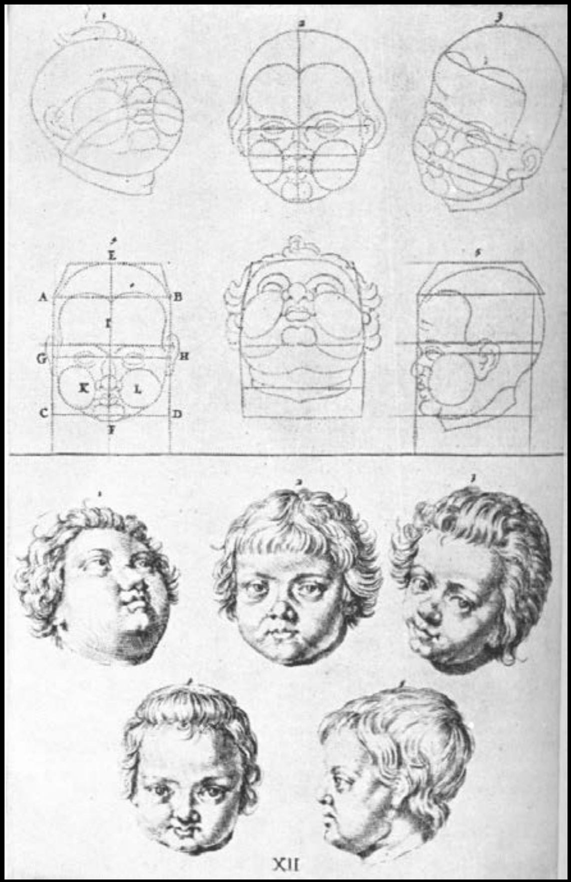
But this *can't* be the whole story, because ***most*** physicsts were ***not*** using the diagrams for perturbative calculations!

Learning to See

Art historian ***Ernst Gombrich***: there is no “innocent eye”; artists begin with “a guess conditioned by habit and tradition.” *Art and Illusion*, 1969

Image is in the public domain.

Fialetti, *Eyes*, 1608



van de Passe, *Putti*, 1643

Image is in the public domain.

So, too, for scientific images: prior habits or traditions can have a long influence on how scientists see the world.

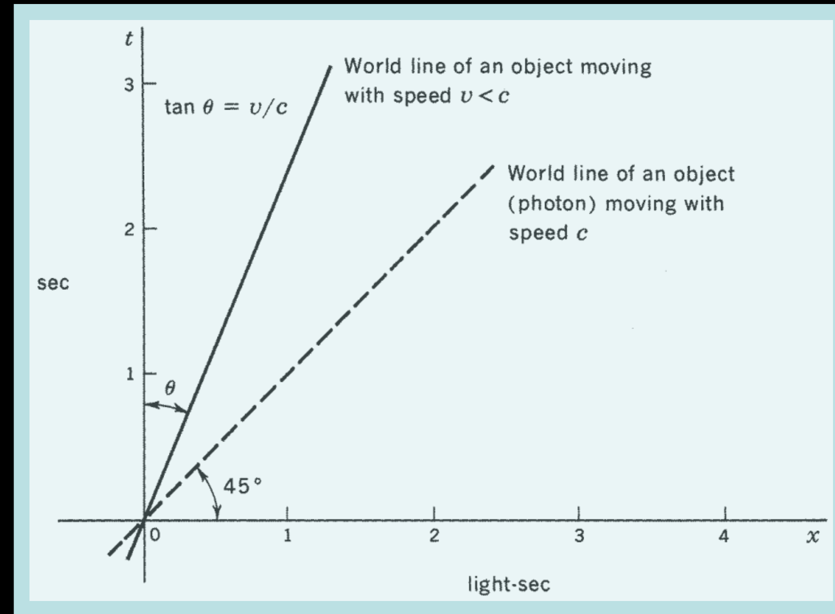
Like the human appendix, these ***pictorial conventions*** sometimes play no clear function; they are ***evolutionary remnants***, left-overs that nonetheless condition how scientists interpret new images and ideas.

Pictorial Conventions

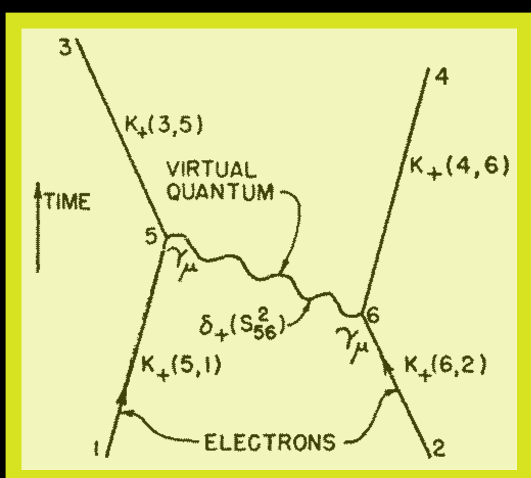
Minkowski diagrams for special relativity: chart objects' motion through space and time.

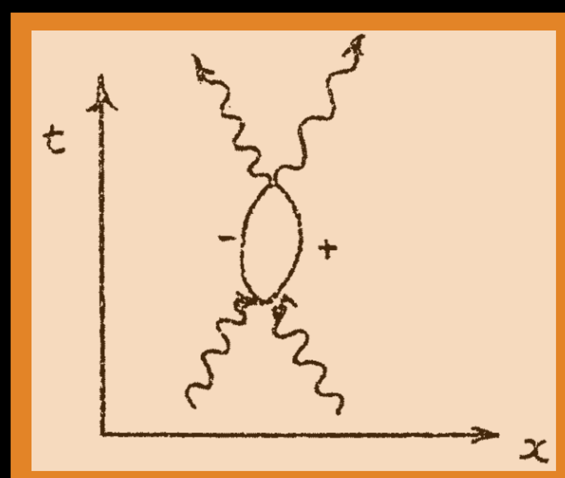
Taught to undergraduates:

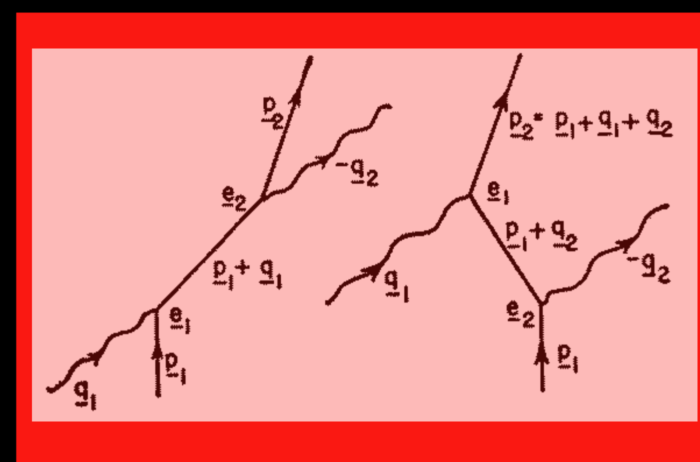
Time runs up, space runs across;
scale c = 1, so light travels on 45˚ diagonals



Feynman consistently followed the same ***pictorial conventions*** for his own diagrams, ***even when working in momentum space***.

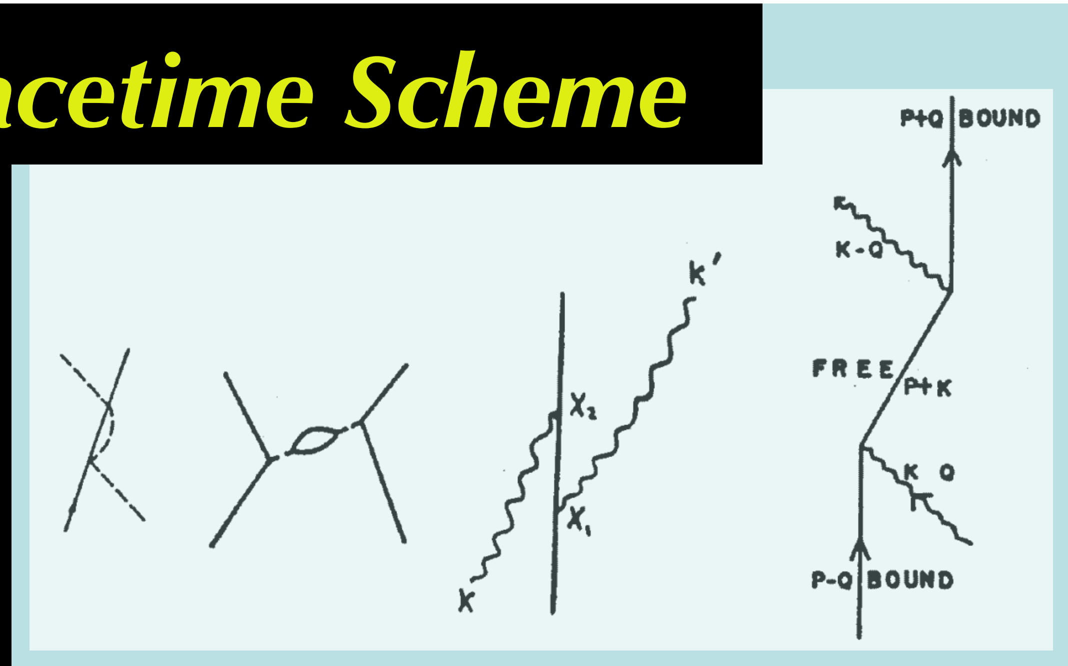




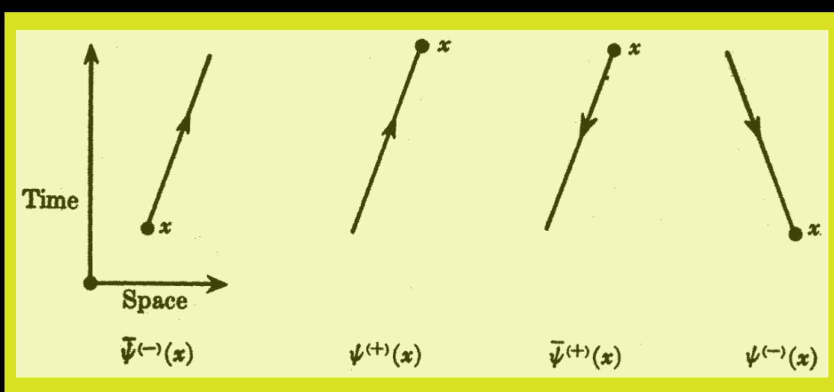


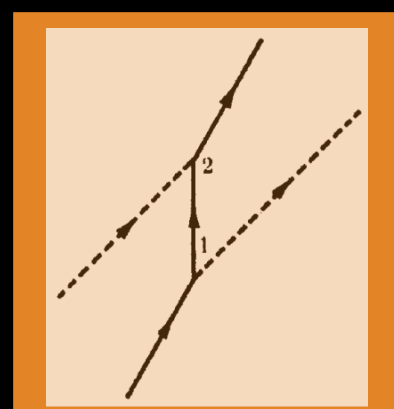
Repetition of the Spacetime Scheme

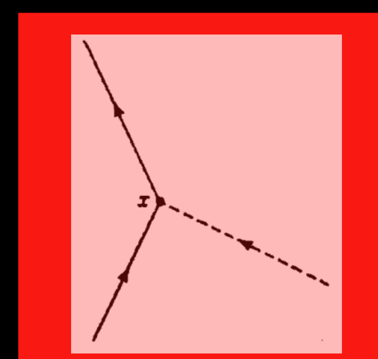
These conventions became common beyond Feynman himself. In these examples, the tilted propagation lines played ***no role whatsoever*** in the accompanying calculations.



Early ***textbooks*** repeated the pattern, often arguing 'against' their own pictures in the accompanying text!

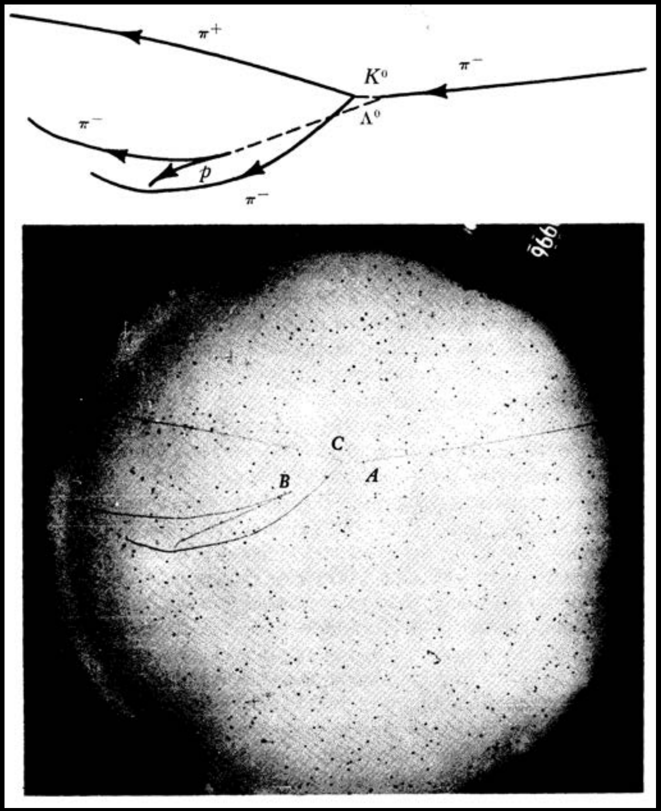




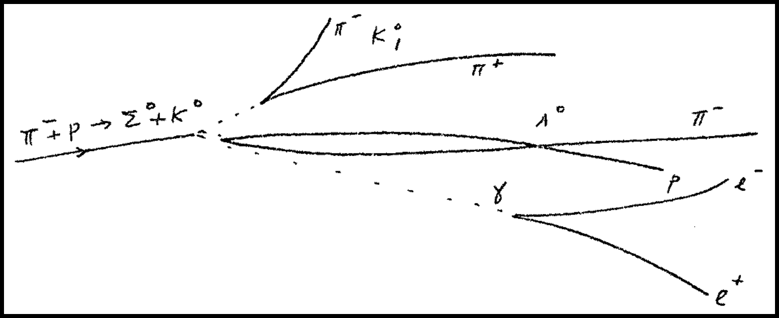


Another Visual Link: Bubble-Chamber Photographs

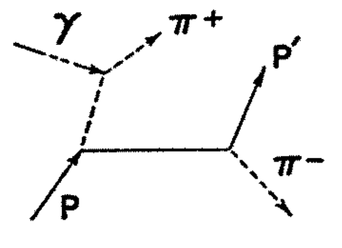
Physicists were *inundated* with bubble-chamber photographs during the 1950s.

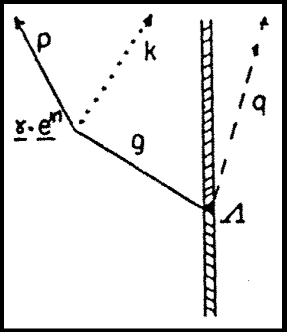


Free-hand reconstructions



Visual affinity far more general than specific Dyson-rules for perturbative calculations.

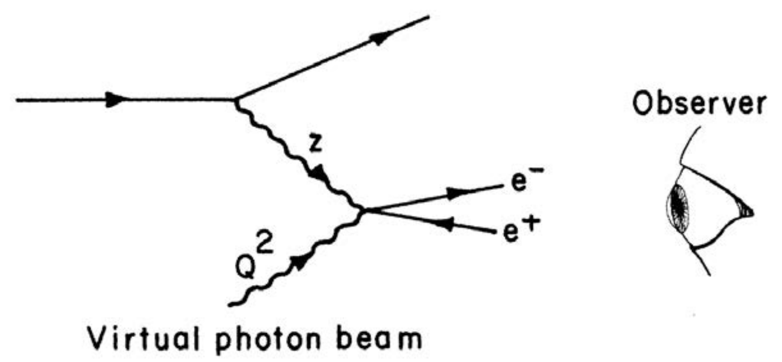


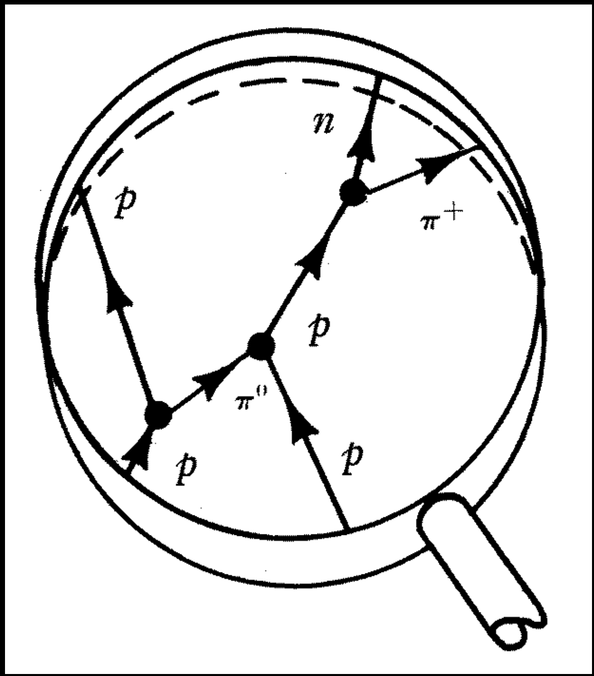


But Are They Real?

"The diagrams are so vividly 'physical-looking,' that it seems a bit extreme to completely reject any sort of physical interpretation whatsoever. […] We will therefore 'talk about' the diagrams as if they were physical, but remember that in reality they are only 'apparently physical' or '*quasi-physical.*'"

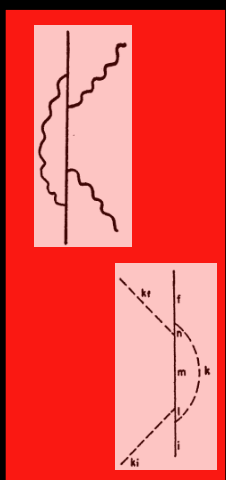
Richard Mattuck, *A Guide to Feynman Diagrams in the Many-Body Problem* (1967)

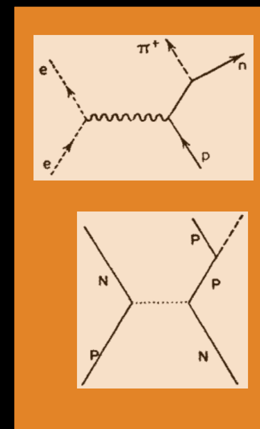


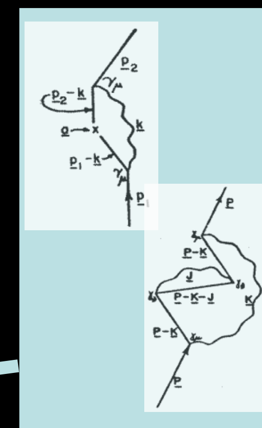


Conclusions: Cascades and Conventions

Scientists must always ***practice*** wielding their ***tools*** — whether the tools are at the lab bench or on the scratch pad.

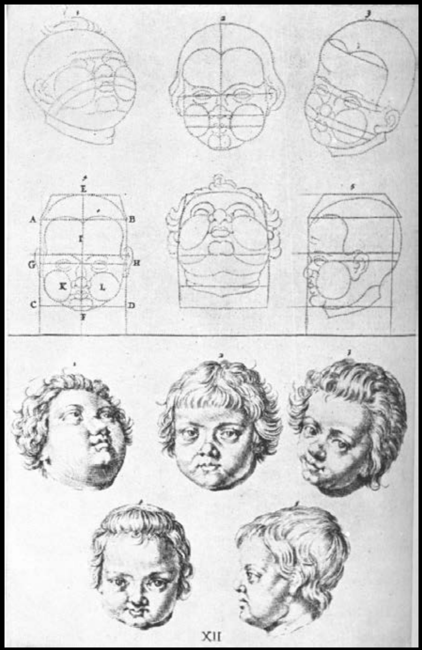




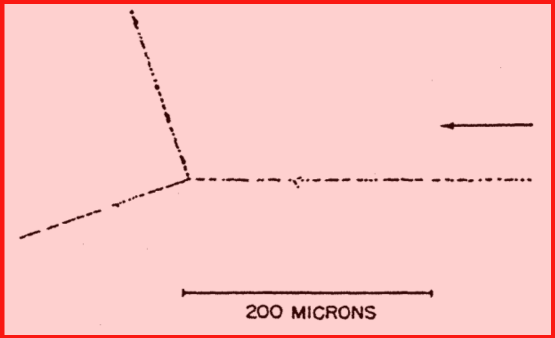


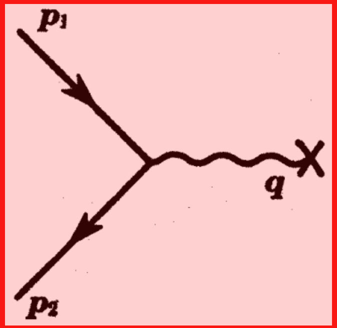
Postdoc cascades spread the diagrams throughout the US and the world.

Staying Power



Scientists' practices will be influenced by the ***habits*** and ***conventions*** they have already learned: there can be significant "pedagogical baggage" even for brand-new techniques.





Feynman diagrams and their users were forged as part of the same pedagogical process.