Richard Feynman
A Life of Many Paths

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Osher Lifelong Learning Institute, UC Irvine, April 6,2012

The Young Feynman

- Richard (Dick) Feynman was born May 11, 1918 in Far Rockaway, Queens, NY.
- His parents were Jewish and from Russia and Poland.
- As a child he was taught by his father to take independent viewpoints on things.
- He repaired radios as a youth, as he could figure out what was wrong with them.
- He learned calculus at 15.
- As a senior in high school, he won the NYU Math Challenge.

Feynman’s Education and the Manhattan Project

- He was an undergraduate at MIT and graduated in 1939.
- He was a graduate student of John Wheeler’s at Princeton, where he already did advanced work on Quantum Electrodynamics (QED), and received his Ph.D. in 1942.
- His physics prowess was becoming well known, and he was brought to the Manhattan Project at Los Alamos to work with Hans Bethe.
- There he became head of computing, and developed important codes and oversaw their parallel computing farm of ladies on calculators.

Dick and Arline

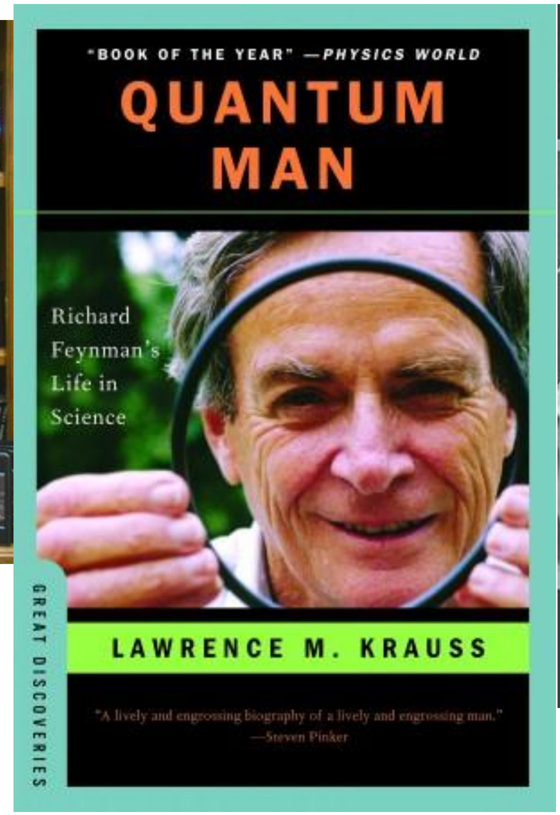
- He married his high school sweetheart Arline Greenbaum when he received his Ph.D., although she was seriously ill with tuberculosis.
- She was very artistic and musical.
- He brought Arline to a hospital in Santa Fe and would visit her on weekends. She died in 1945.
- This period was portrayed in the movie “Infinity” in 1996, starring and directed by Matthew Broderick.

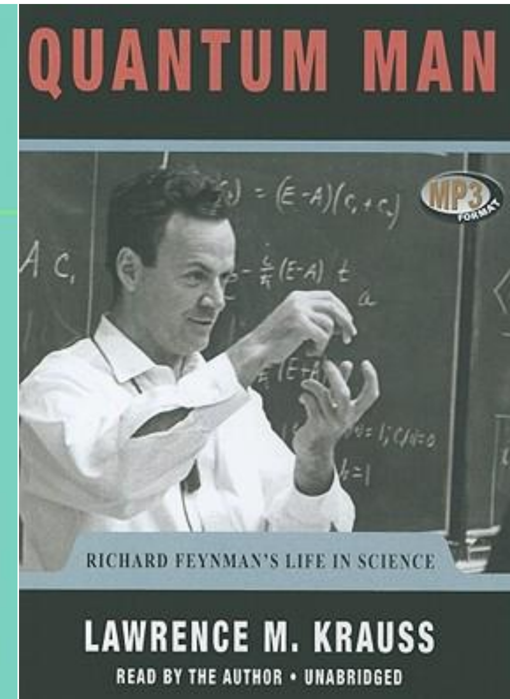
Niels Bohr, Oppenheimer, Feynman, Enrico Fermi

Quantum Man by Lawrence M. Krauss

Feynman

Larry Krauss





Feynman and Path Integrals

- I read *Quantum Man* by Lawrence Krauss for the story of the physics that Feynman developed and worked on.
- After the war, Feynman was recruited by many universities and decided to go to Cornell to work with Hans Bethe.
- There he developed his new Path Integral formulation of Quantum Mechanics.
- Feynman didn’t really use this to rigorously develop his diagrams or rules, so we put that in an appendix.
- We do teach the Path Integral formulation in graduate courses to show students how Feynman rules can be derived, however.

Light as Waves and Particles Called Photons

- The connection of particle and wave properties of light was discovered by Max Planck.
- He connected the energy E of the particles of light, called photons, with the frequency of their wave oscillations, ν, by

  E = $h\,\nu$ where h is called Planck's constant.
- This is also the relation used by Einstein in explaining the photoelectric effect, where single electrons are ejected from a solid when light hits it.

The Scale of Quantum Mechanics

- We will use a more convenient quantity "hbar", where

  $\hbar = h \,/\, (2\,\pi)$.

- Since $\hbar$ usually occurs multiplied by the speed of light c, we show their combined values in useful units:

  $\hbar$ c = 0.2 GeV fm = 2 keV A^0.

- A Fermi, fm is about the size of a proton, and a GeV (billion electron Volts) is about the mass of the proton.
- An Angstrom A^0 is about the size of an atom, and a keV is a scale for energy levels of electrons in heavy atoms.

Relativity and Quantum Mechanics

- The first great discoveries of combining relativity and QM was found by P. A. M. Dirac, which in his Dirac equation discovered both antiparticles, and that electrons had spin 1/2, in units of $\hbar$.
- Previous QM work showed that orbital angular momentum in atoms had only integer values, 0,1,2,3, etc. in units of $\hbar$, that classified atomic levels.
- The spin ½ electron, means that no two electrons can occupy the same state, and leads to the shell model of atoms, the periodic table, chemistry, and eventually, life.
- This is called the Pauli Exclusion Principle.

Paul Dirac and Antiparticles with Negative Energy

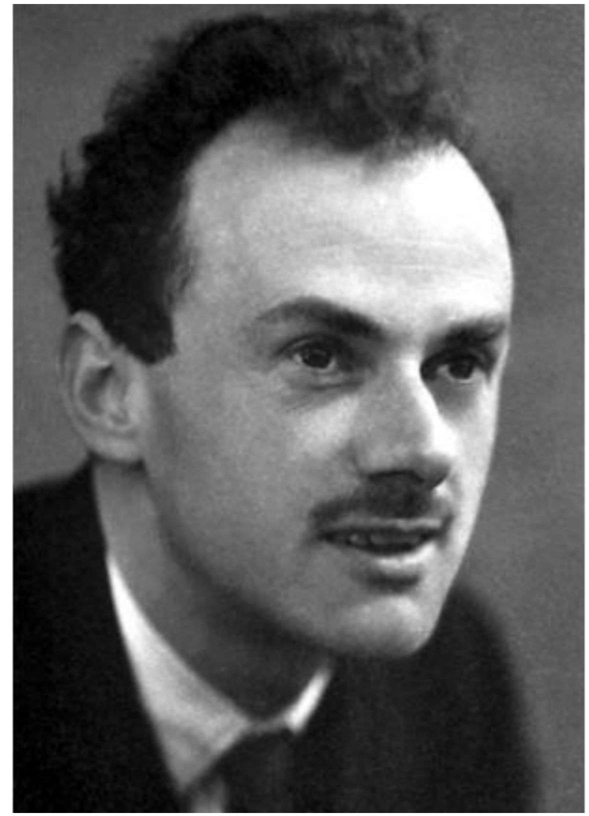
The Relativistic Energy Momentum Relation is:

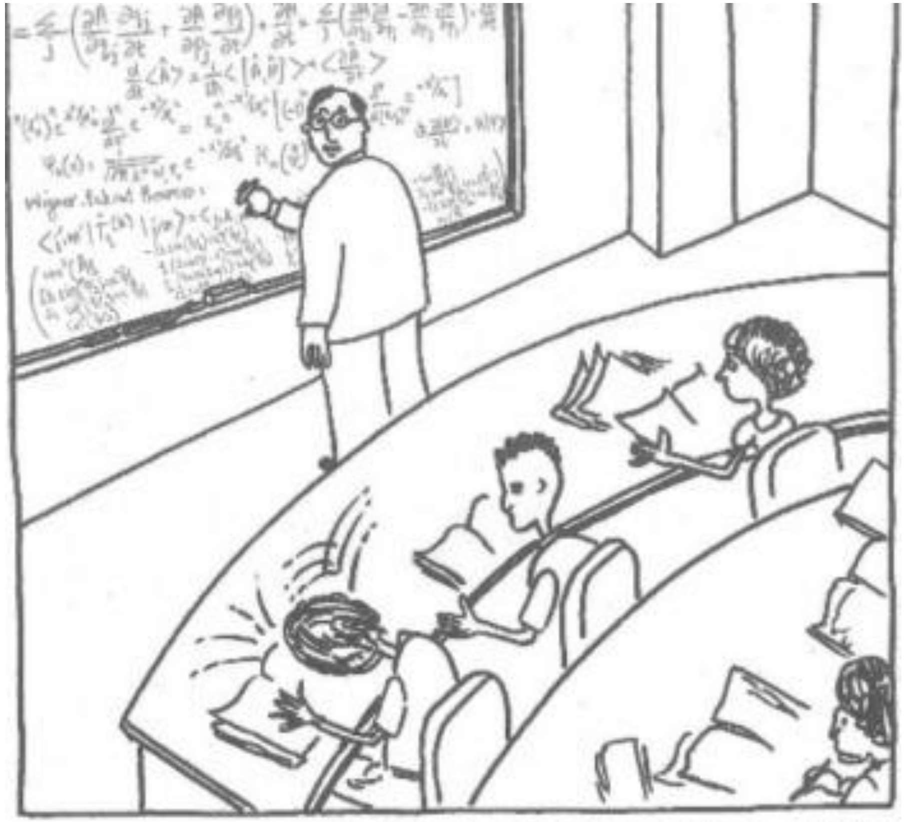
$E^2 = (mc^2)^2 + p^2c^2.$

Note, at rest, the momentum p=0, and therefore,

E= $\pm mc^2$**. The negative energy solutions are those for antiparticles, since they also have the opposite charge from the positive energy solutions.**

Paul Dirac



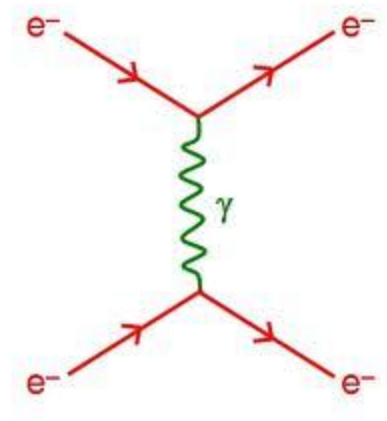


THE INSTRUCTOR OF QUANTUM MECHANICS STOPPED WRITING ON THE BOARD WHEN HE HEARD A LOUD THUD... ANOTHER BRAIN IMPLODED!

Feynman Diagrams

- Feynman formulated the quantum theory of interacting electrons and electromagnetic fields called Quantum Electrodynamics in his path integral approach.
- The electromagnetic fields could act as particles in the photoelectric effect, as explained by Einstein. These are called photons.
- By working many examples of processes, Feynman realized a great simplicity: that he could formulate a set of rules for writing the results without deriving each one.
- This opened up the ability to calculate to everybody.
- Feynman also drew diagrams that showed physically how the processes occurred.
- This has been applied to all of the new theories of current and proposed new particles and interactions.

Feynman Diagrams fc



•The lowest order diagram in the strength of the interaction, which is the electron charge "e". For exchange of a photon, each connection is given by e, and the product is scaled to the dimensionless constant

$\alpha = e^2/\hbar c = 1/137.036$

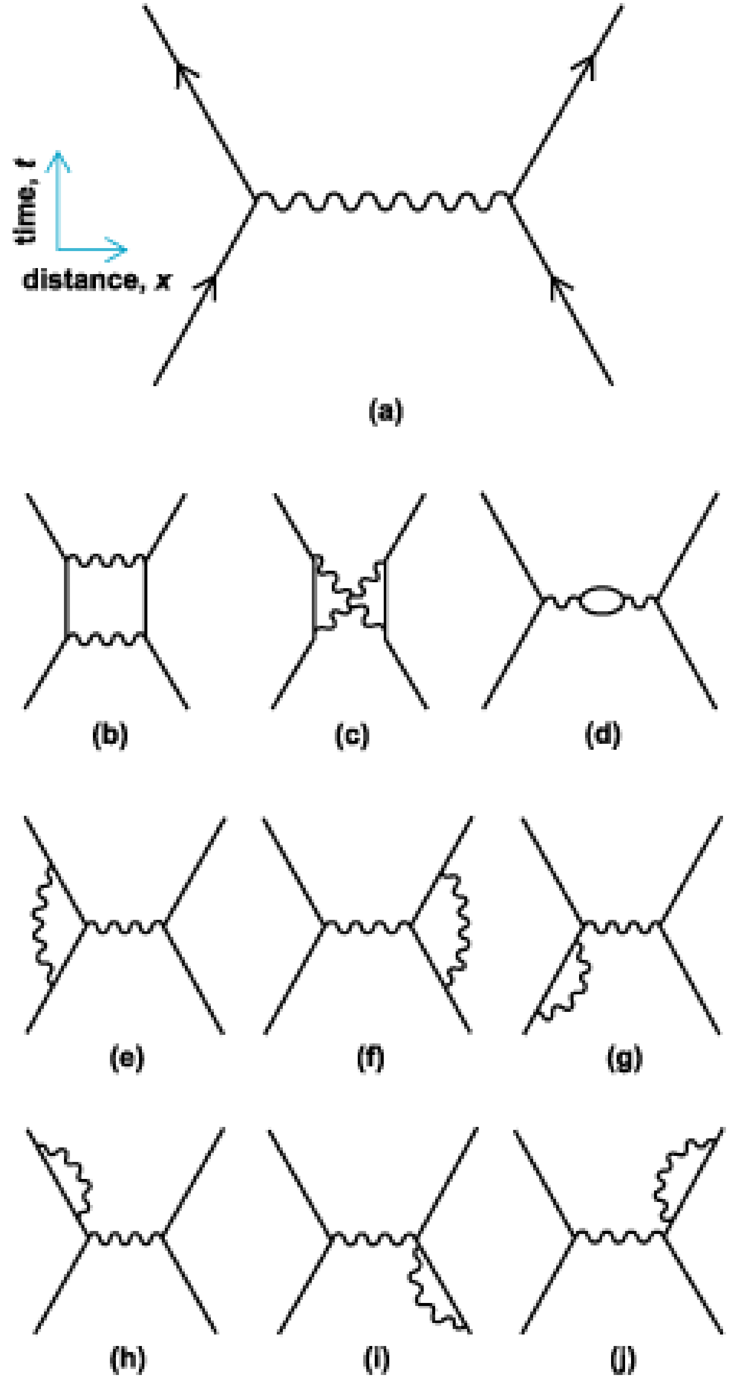
which is called the fine structure constant.

•The processes in QED are an expansion in powers of α with an extra exchanged photon for each additional order or power of alpha.

First and Second Order QED Feynman Diagrams

for electron-electron scattering.

Second order diagrams have two photons exchanged.

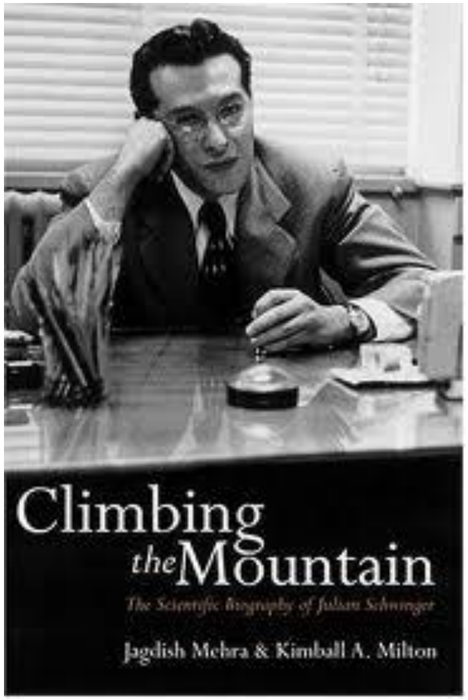


Feynman Rules for QED

- Feynman's rules give a free particle solution to the Dirac equation for each incoming and outgoing free electron, and a solution to Maxwell's equations for each free photon.
- At each vertex of an electron with a photon is a photon source J, called an interaction.
- Feynman propagator functions connect each exchanged photon to its current source and absorption vertexes, and each electron between photon.
- There is also a "Dirac delta function" that guarantees that energy and momentum are conserved exactly at each vertex.
- Because of that, energy and momentum are conserved for each diagram from start to finish.
- The oft made statement that energy can fluctuate in a process should really be that the intermediate particles are virtual, and don't have the right connection of energy and momentum to escape as free particles.

Freeman Dyson, Julian Schwinger, and Sin-Itiro Tomonaga

Freeman Dyson showed in 1948 that Feynman's diagrams and rules for calculation were the same as the Field Theory approaches of Julian Schwinger and Sin-Itiro Tomonaga.



Antiparticles as Negative Energy Solutions

- In these rules, Feynman interpreted the negative energy solutions as particles moving backwards in time.
- This got rid of the earlier interpretation where antiparticles were holes in a filled sea of negative energy particles that permeated all of space-time, the so-called Dirac sea.
- In propagation of photons between the source electron and the absorbing electron, both time orderings of emission and absorption could be included relativistically, in a “propagator” function that was developed in Feynman’s thesis with John Wheeler.
- These had also been developed independently by E. C. G Stueckelberg, but not exploited as Feynman did.
- Feynman Video “Go Somewhere Else”
- Hans Bethe on Feynman and Schwinger

Feynman Moves to CalTech

- In 1950, Feynman was offered a position at CalTech.
- Before going there he took a half year off to relax in Rio in Brazil, where he taught Physics and learned to play the bongo drums.
- From 1952 to 56 he was married to Mary Louise Bell, but that did not turn out to be a good match, since he worked all of the time.
- After that, on a trip to Switzerland, he met the British Gweneth Howard, and hired her as an au pair.
- He married her in 1960, and they had a son Carl and an adopted daughter, Michelle.

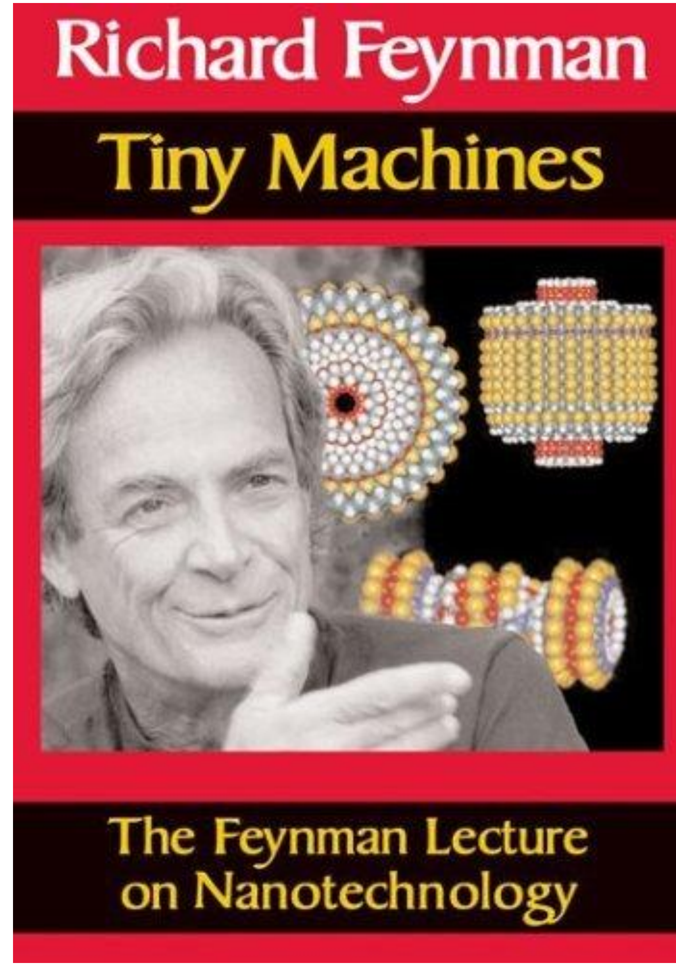
Feynman’s Van and Family

Superfluid Helium, Superconductivity and Weak Interactions

- Besides particle physics, Feynman worked on Superfluid Helium. He treated it as a “Bose-Einstein” condensate, in which all He atoms of zero angular momentum could be in the same state and act alike at low temperatures as free particles.
- He also worked on Superconductivity, where he discovered and worked on vortices as the excitations in the superconductor.
- With Murray Gell-Mann at CalTech, he formulated the theory for the weak interactions, which was like QED, but including another current that violated parity maximally, called the “V-A” theory. It used only left spinning electrons, and right spinning positrons.

Feynman and Nanotechnology

- In 1959 Feynman gave a lecture speculating on manipulation and building machines on the atomic or molecular scale, which is now known as nanotechnology.
- The title of the talk was "*There's Plenty of Room at the Bottom*".
- Today we can see and move individual atoms with atomic force microscopes.
- He also covered microscopic data storage, microscopic motors, and quantum engineering.



The Feynman Lectures

- By 1961, Feynman got very interesting in teaching, and presenting his own unique outlook on basic physics subjects.
- He taught Freshman and then Sophomore physics, and his notes were compiled by Robert B. Leighton and Matthew Sands
- The lectures were not only complete, but added analyses of many phenomena in a simple, Feynman way. You can almost hear Feynman speaking in the syntax used.

The Feynman Lectures

- The lectures were published as the Feynman Lectures in Physics in three red volumes (list copied from Wikipedia):
- Volume 1: Mechanics, radiation and heat.
- Volume 2: Electromagnetism and matter.
- Volume 3: Quantum mechanics.
- Abbreviated editions:
  - Six Easy Pieces (1994)
  - Six Not-So Easy Pieces (1998)
  - The Very Best of the Feynman Lectures (Audio, 2005)

“The Character of Physical Law” Messenger Lectures

- In 1964 he went to Cornell to give seven Messenger lectures, which were recorded on film. They are titled “The Character of Physical Law”.
- In 2009, Bill Gates obtained the rights to these and put them on the web for free as “Project Tuva”. They can be viewed on Windows with special software including notes. The lectures are titled (copied from Wikipedia):
- The law of gravitation, an example of physical law
- The relation of mathematics to physics
- The great conservation principles
- Symmetry in physical law
- The distinction of past and future
- Probability and uncertainty - the quantum mechanical view of nature
- Seeking new laws
- Start of Feynman Lecture on Quantum Mechanics

Feynman Lectures on Gravitation

- In 1962 to 1963, Feynman turned to Gravity, which had only been dealt with classically before.
- He quantized gravity, with the graviton being the quantum of the gravitational field radiation.
- He laid out the Feynman rules for gravity and did the second order calculation, discovering the bad infinities, that have only been dealt with now with supersymmetric string theory.
- He also realized the possibility of a zero net energy universe, which is now part of the inflation model of the start of the universe.
- His lectures at CalTech on this were not published as a book until 1995.

1965 Nobel Prize in Physics

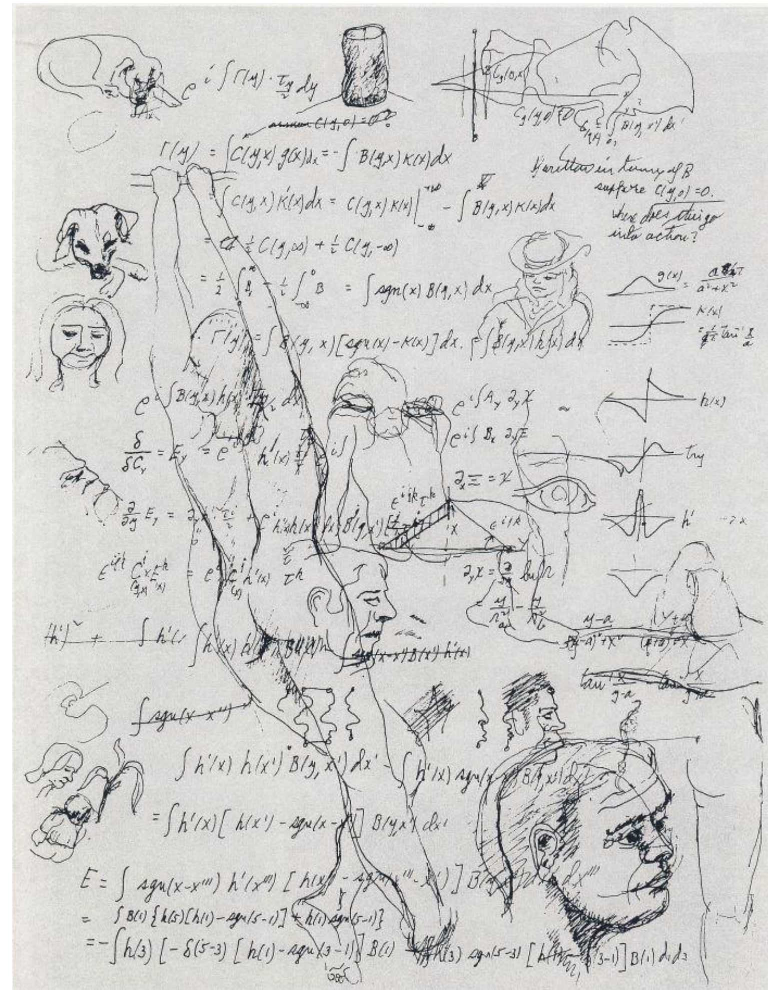
In 1965 the Nobel Prize in Physics was awarded for the development of QED to Feynman, Schwinger, and Tomonaga.

Feynman's speech on the history of his development of the theory is on the Nobel website.

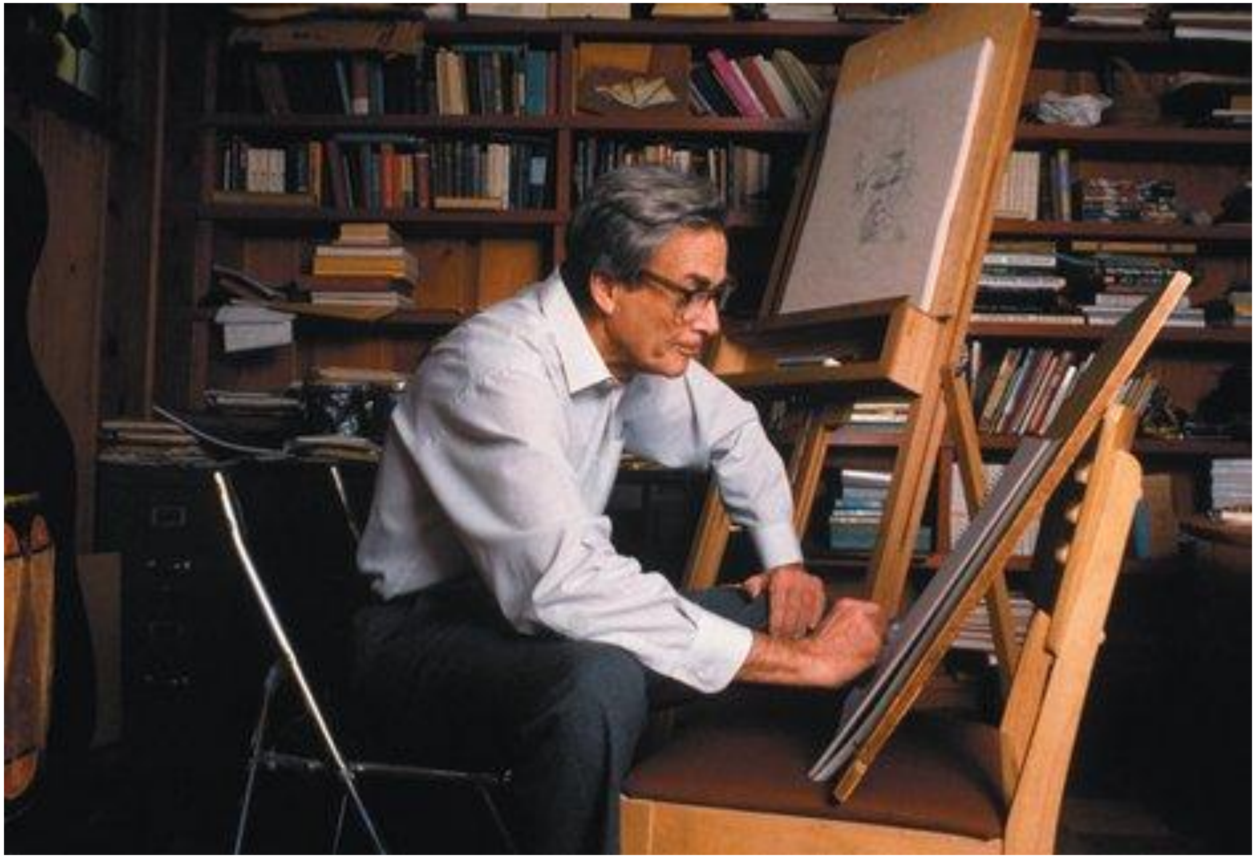
Feynman’s House in La Mision, Baja, From the Nobel Prize

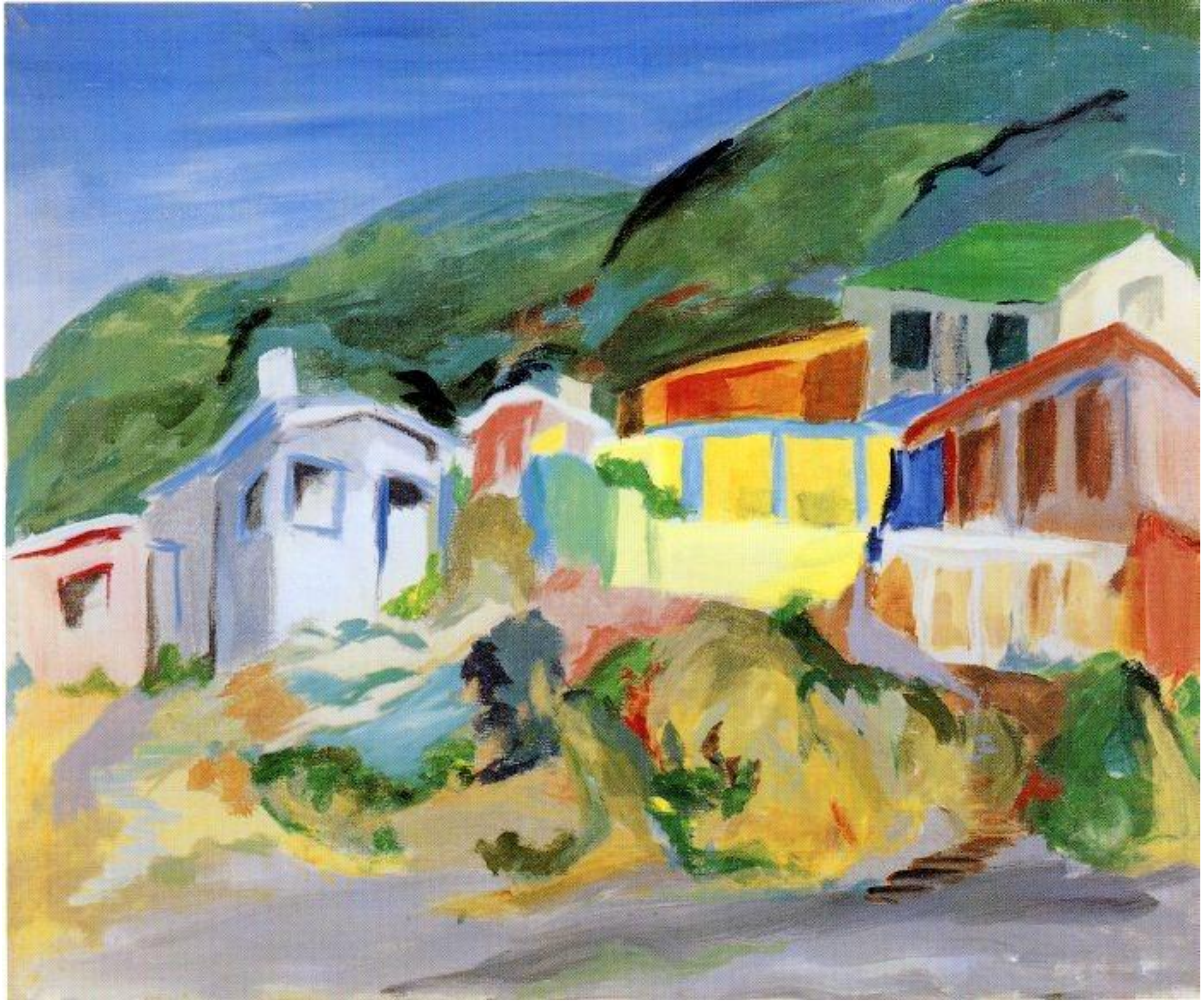
Feynman takes up Drawing

- Around 1962 Feynman took up art to express the deep emotions that he felt about nature.
- His drawings can be seen on the www.museumsyndicate.com website.
- He used the pseudonym Ofey after the French “au Fait”, meaning “it is done”.
- This one is called “Equations and Sketches”.



Feynman Drawing

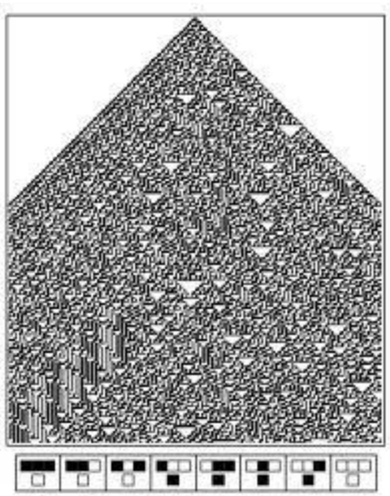


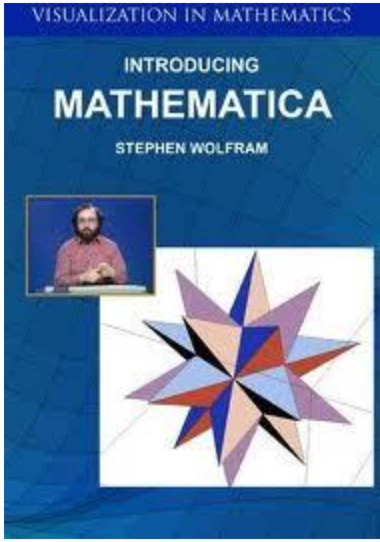


[Feynman Playing Bongo Drums with Ralph Leighton]

Feynman and Computing – Stephen Wolfram

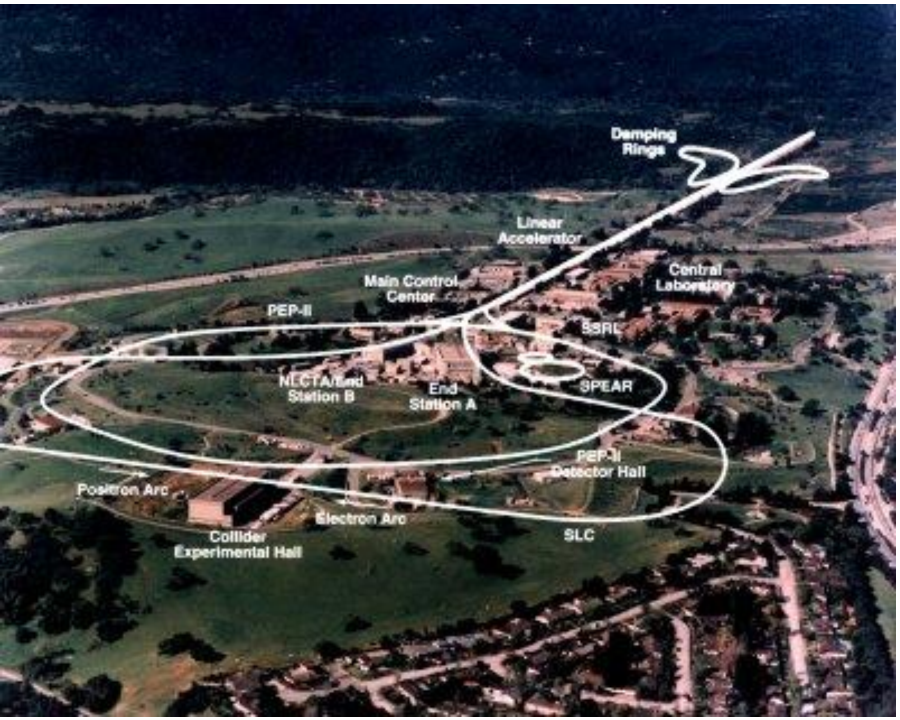
- From 1981-85 Feynman worked on questions of computer simulation, parallel processor computation, pattern recognition, and computability of physics problems.
- He also wrote about quantum element computation.
- He worked on cellular automata or schemes of cellular nodes evolving in time with certain rules.
- He helped inspire Stephen Wolfram to program a computer to do algebra, which became the Mathematica software and company.
- This has expanded to the all data app called "Wolfram alpha" on iPhones, and a principal source for Siri.



The Stanford Linear Accelerator Center (SLAC) that scattered electrons off of protons at high energy.

The two mile linear electron accelerator

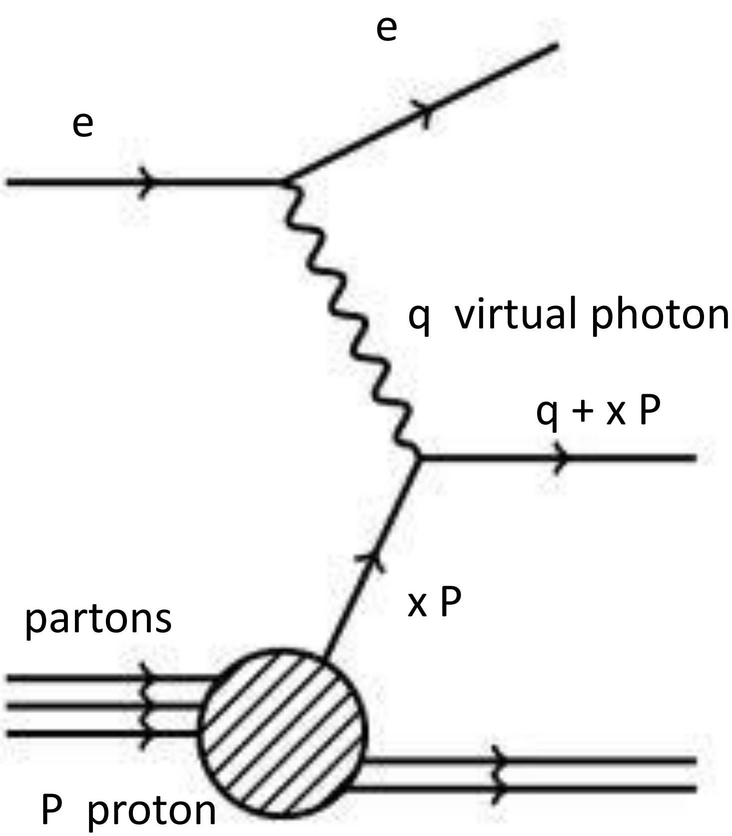


Magnets and detectors for the scattered electrons

Frozen Pancakes and Partons

- SLAC was scattering electrons off of protons at high energy, or short wavelength, of the virtual photons given off by the deflected electrons.
- Feynman realized that passing a proton at high speed meant that the proton would Lorentz contract and look like a pancake.
- Also, clocks in the proton would appear to slow down, called time dilation, so the constituents of the proton, called *partons*, would appear to not be interacting, and would act as free particles, frozen in place.

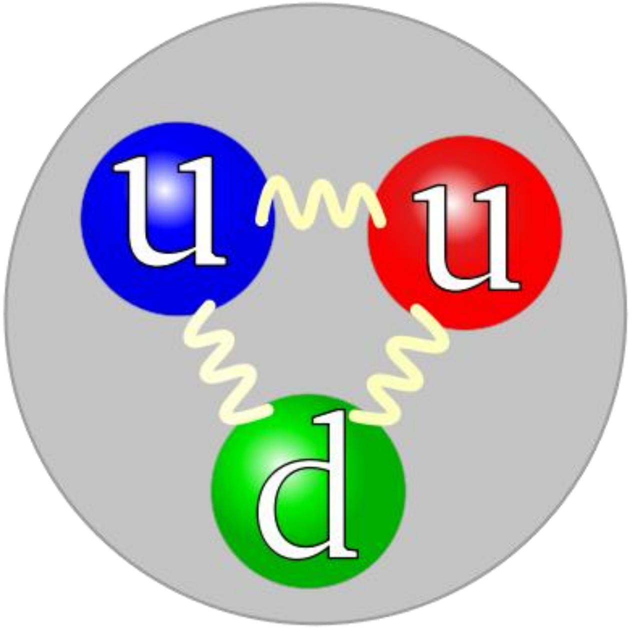
Scattering of Electrons by Partons via Photons



- The process would essentially take an instantaneous picture of the proton at high resolution, with the constituents frozen.
- The momentum of the partons was along the same direction as the proton, but with a fraction of the total momentum called x
- $P_{parton} = x P_{proton}$, where x runs from 0 to 1.

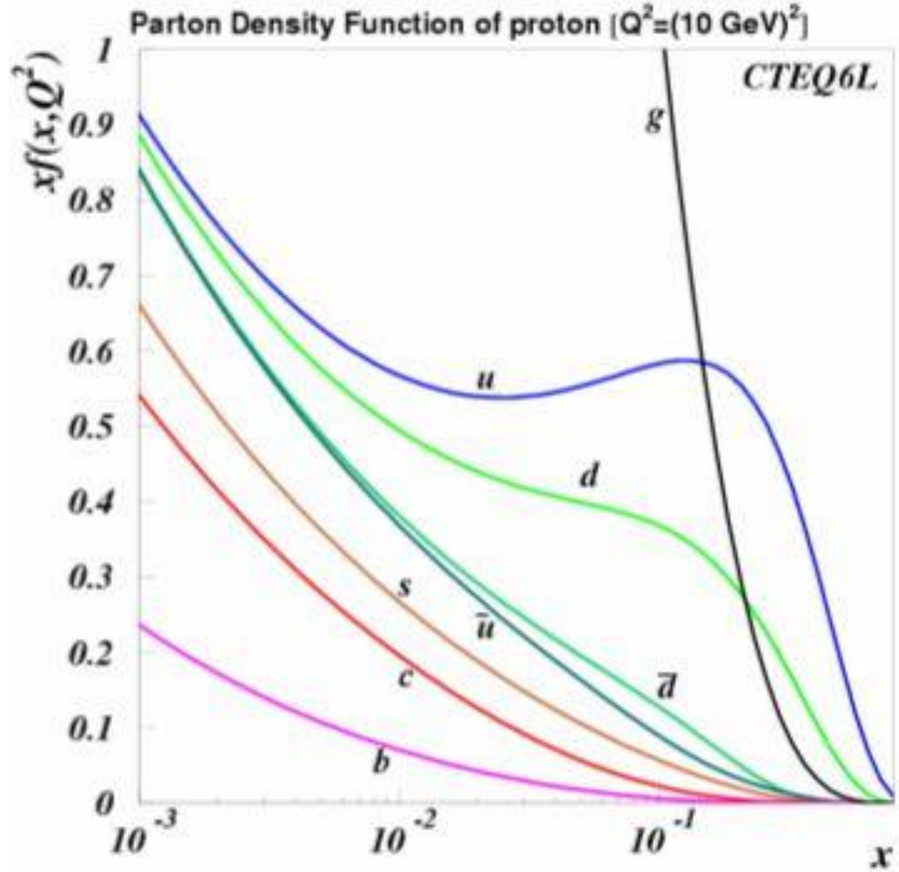
Partons as Quarks

- Since the scattering was due to photons, the amount of scattering or effective "cross section" of the proton for scattering, would be due to the *square* of the charge of each parton.
- The fractional (+2/3 e) charge for an up quark parton, and (-1/3 e) for a down quark parton, was then revealed, and the partons could be identified as Gell-Mann and Zweig's quarks.
- Rather than just a mathematical underpinning of particle symmetries, the quarks were real particles!



Parton Distribution Functions

- Up and down quarks in the proton forming its core are called valence partons (uud), and have the parton x distributions *u* and *d* in the figure (multiplied by x).
- Virtual gluons can also create pairs of u, d, and s quarks and antiquarks, forming a sea of quarks, with a distributions labeled by $\bar{u}$ and $\bar{d}$ with bars, and *s*.
- Gluons frozen in the picture of scattering have the distribution *g*, which show up in strong interaction scattering.



SLAC Nobel Prize in 1990 for Proton Structure by Richard Taylor, Jerome Friedman, and Henry Kendall

Other Discoveries of Free Particle Scattering

- The effective results of the free parton scattering were previously inferred through an abstract Current Algebra approach by James Bjorken at SLAC before the results came in. So it is called Feynman-Bjorken scaling.
- Feynman's genius of simplicity was to see that the scattering was due to a free parton, and that the value for x could be derived from the scattering energy and momentum in a few lines.
- The parton distribution functions are also used in proton-proton scattering, and in all high energy processes.

Personally Relevant SLAC Pictures

SLAC Theory conference room that also used to be my office as a graduate student

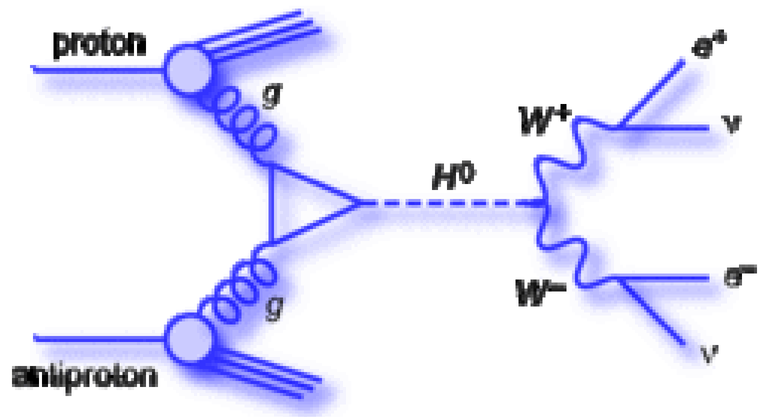
UCI Physics Ph.D. Jonathan Dorfan, who became director of SLAC

My Thesis Advisor Sid Drell, and Former Lab Director and Nobel Laureate Burton Richter (1976). The text by Bjorken and Drell became the standard text for Feynman Diagrams and the Rules of QED.
As a grad student, you worked hard or else.

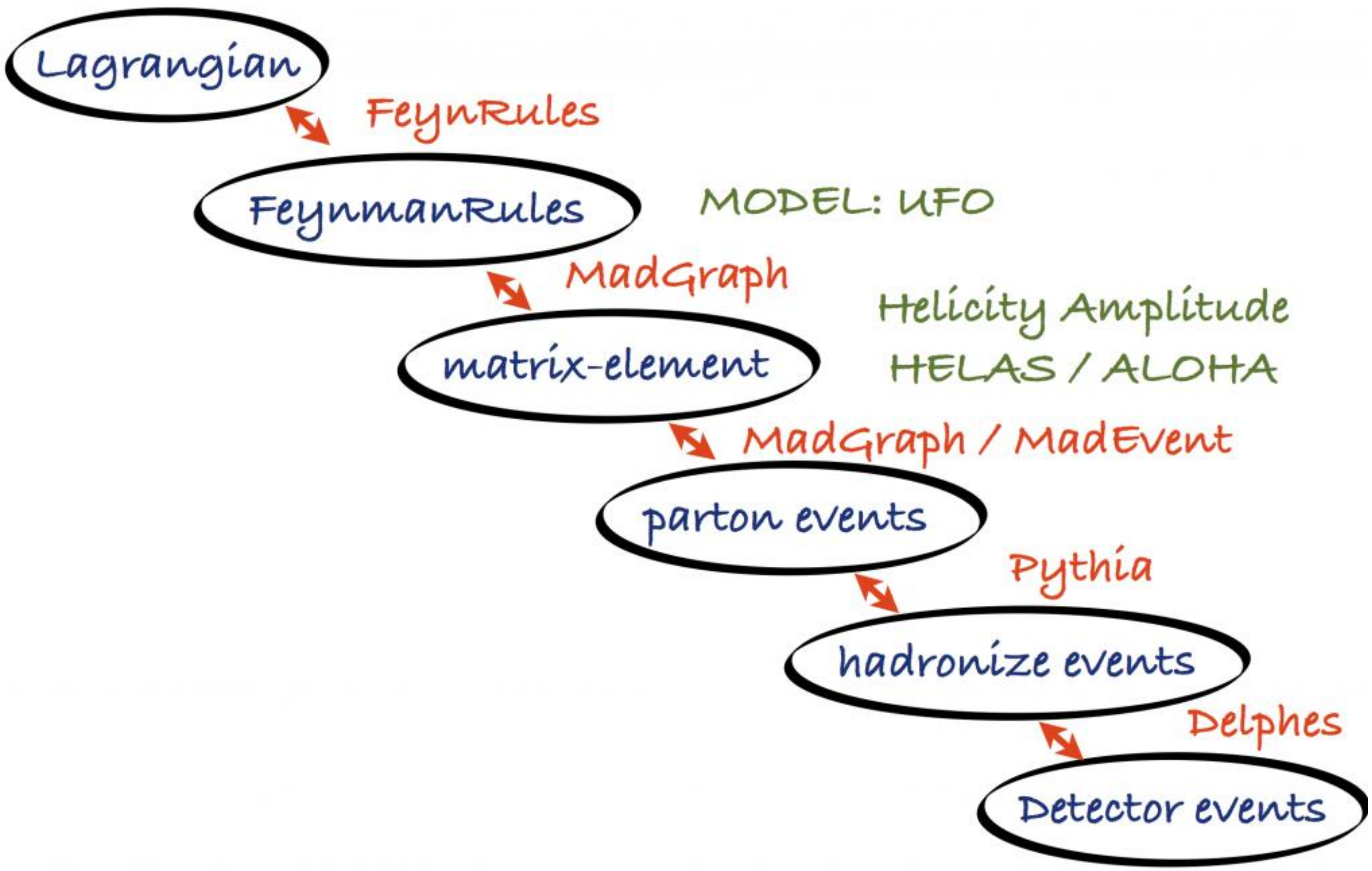
Feynman Diagrams Today

- Today, Feynman Diagrams are used for Weak, Electromagnetic and Strong interactions at high energy.
- They can be calculated to high order using formulas based on the preceding order.
- They are now generated by computer and calculated by computer.
- Monte Carlo programs are written for various experiments that calculate the number of events that are expected in an experiment from the diagrams.

Higgs from gluon fusion



Automated Theory to Experiment via Feynman Diagrams



The Challenger Space Shuttle Rogers Commission

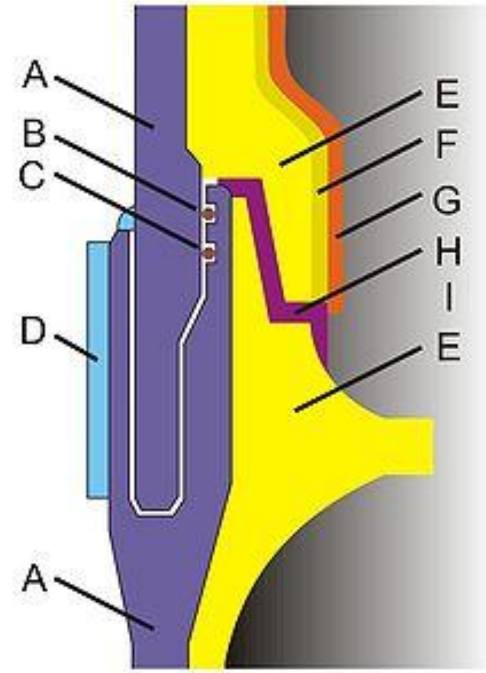
- In January 18, 1986 the space shuttle Challenger exploded while in the booster rocket phase, and Feynman was appointed to the Rogers Commission to examine the cause and increase the safety of the space shuttle.
- The solid booster rocket was actually put together from several pieces, sealed by two O rings around the circumference.
- Engineers had pointed out problems with this to management, but they delayed in instituting fixes.

Feynman’s Demonstration

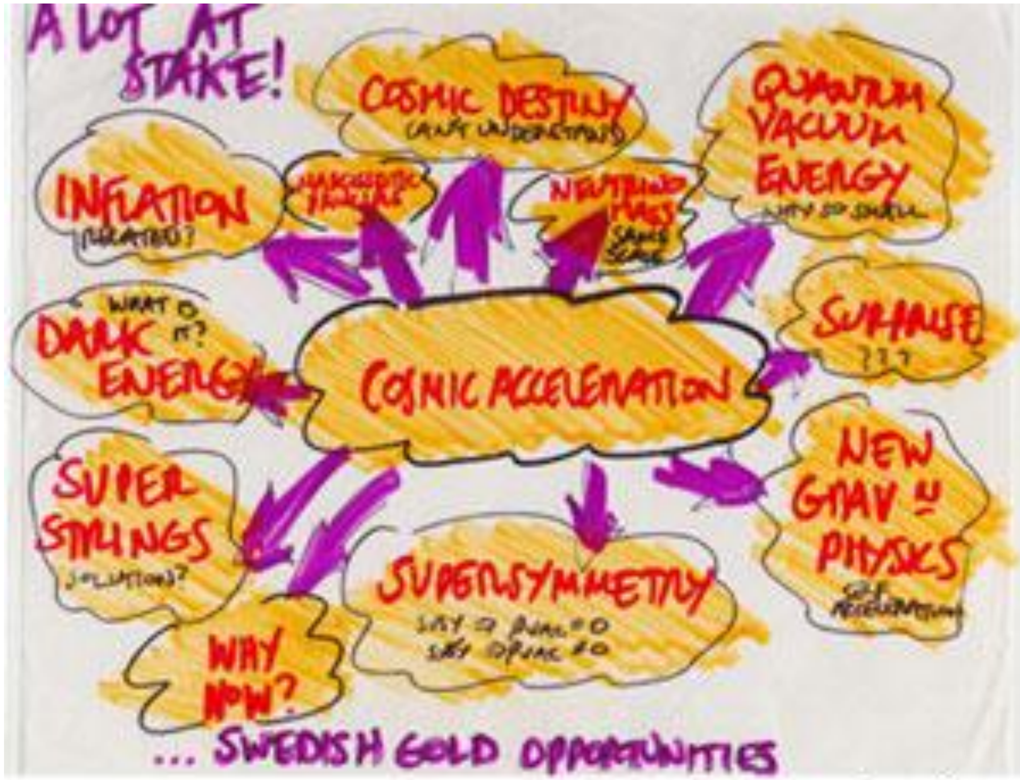
- But the day of the launch the temperature was as low as 8^0 F.
- In the Congressional hearing in February, Feynman rustled together a small O ring and ice to show how it would freeze and not expand to seal the joints.
- Feynman accepted this responsibility even though he was already very ill with cancer.

Feynman’s Report on Safety and Management

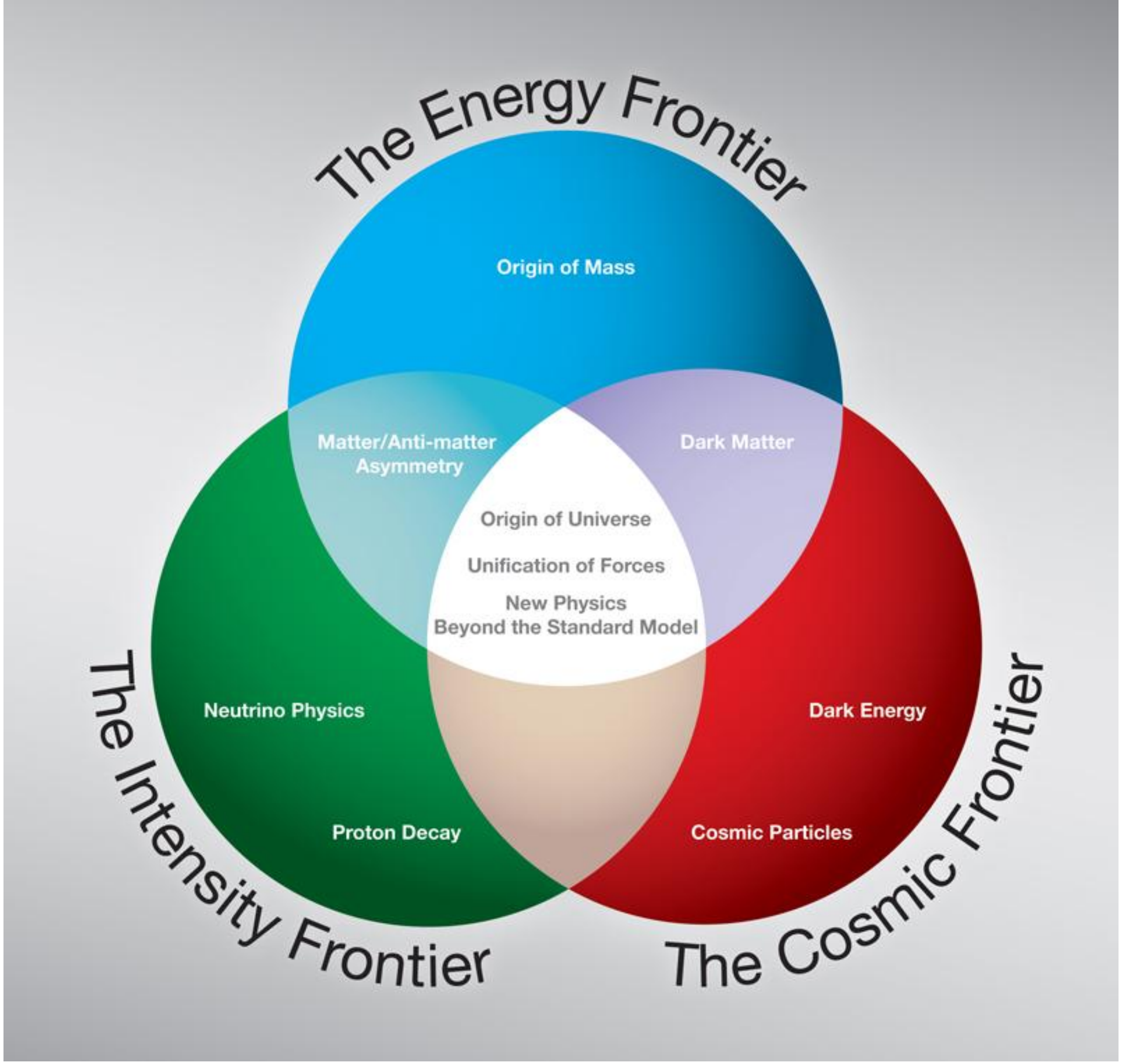
- The joints also were pulled apart by twisting and expansion of the booster segments.
- This caused the escaping flame to burn the lower booster attachment, open a hole to the hydrogen tank in the external fuel tank, and the booster to detach, resulting in disaster.
- Feynman also wrote an appendix F to the report where he discussed problems with estimating safety levels and examined the safety of all of the systems of the shuttle.
- He also pointed out that management was always increasing the safety levels determined by engineers by factors of a hundred or a thousand.



How Feynman Viewed Physics:
as a lot of interconnected subjects that affected each



Cosmic acceleration
Image credit: Michael Turner


The Energy Frontier
Origin of Mass
Matter/Anti-matter
Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics
Beyond the Standard Model
Neutrino Physics
Proton Decay
Dark Energy
Cosmic Particles
The Intensity Frontier
The Cosmic Frontier

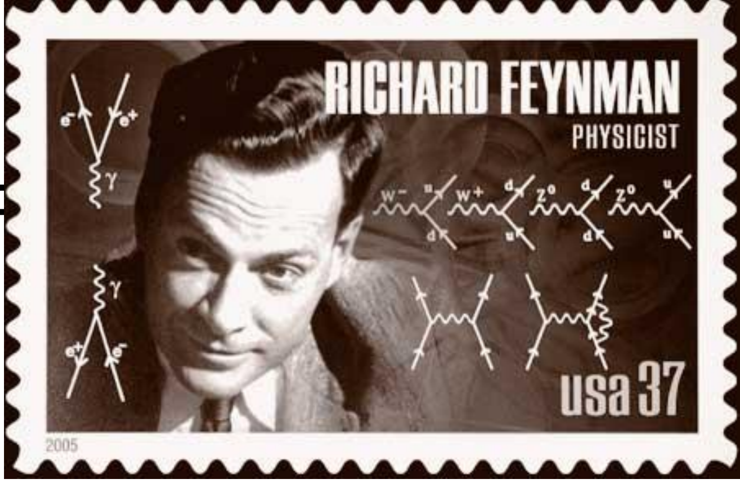
Feynman's Departure and Legacy

- Feynman contracted a rare cancer in 1979.
- In 1987 he had a recurrence and another rare cancer.
- Despite this he kept working out of interest.
- He died in on Feb. 15, 1988 at the age of 69.
- Feynman on Science and Living With Uncertainty
- It is clear that Feynman inspired a spirit of independent thinking in all fields, and a spirit of striving for and finding the simplest ways of understanding and explaining science.

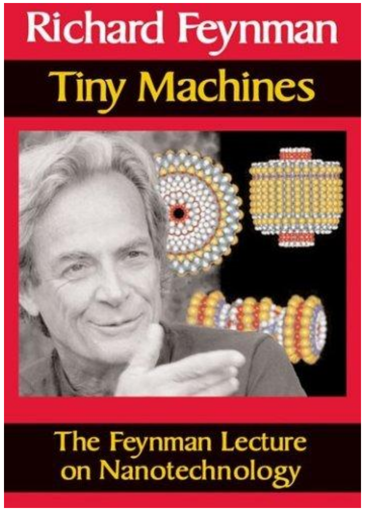
Feynman Web Sources

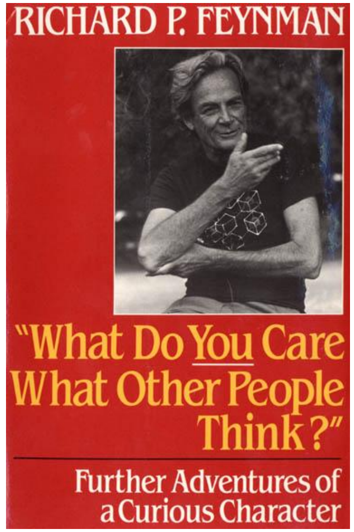
- Googling Feynman will turn up many sites devoted to him as well as Wikipedia articles and the Wikiquotes site.
- There are also interviews with him on YouTube.
- We already mentioned the Messenger lectures on the Tuva Project site.
- On TED there are lectures from a conference from people who knew Feynman.
- CalTech Photo Archives has 277 pictures of Feynman (pay for use)
- Also on the site where Gell-Mann has 200 short biographical segments, there are comments on Feynman as well.

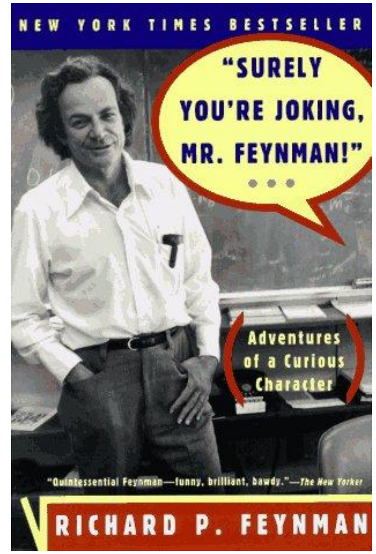
Books by and about F

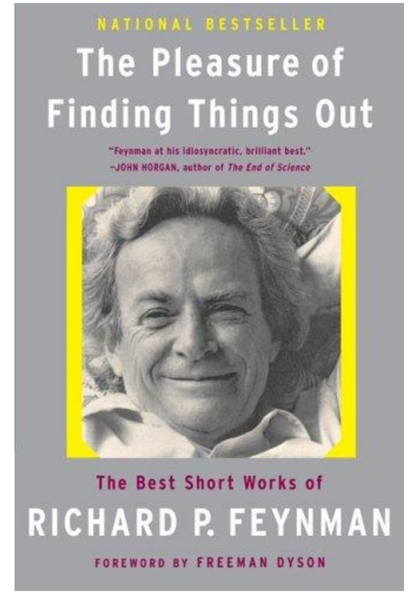


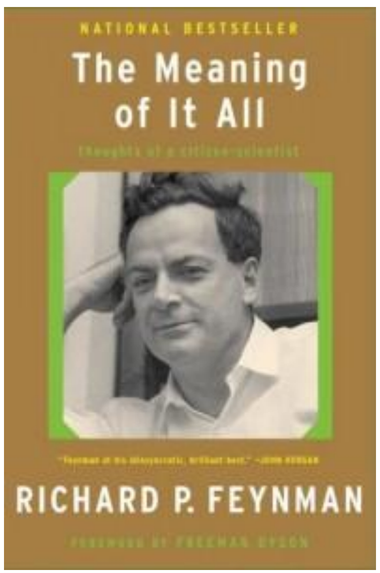
- There are many books that he wrote and that were written about him that are shown on the next slides. Feynman was a great story teller.
- Alan Alda studied Feynman and gave a play “QED” in 2001.
- In 2005 there was an opera called “Feynman”.
- In 2005 there was also a Feynman stamp, above.

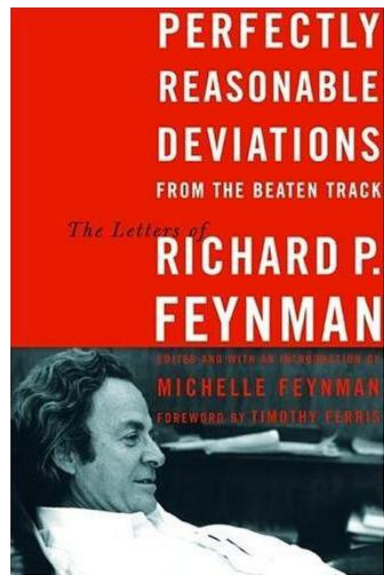


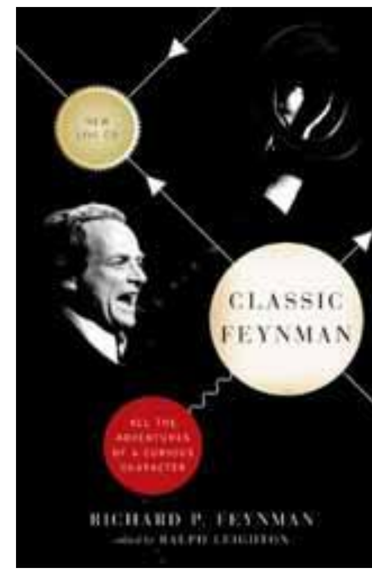




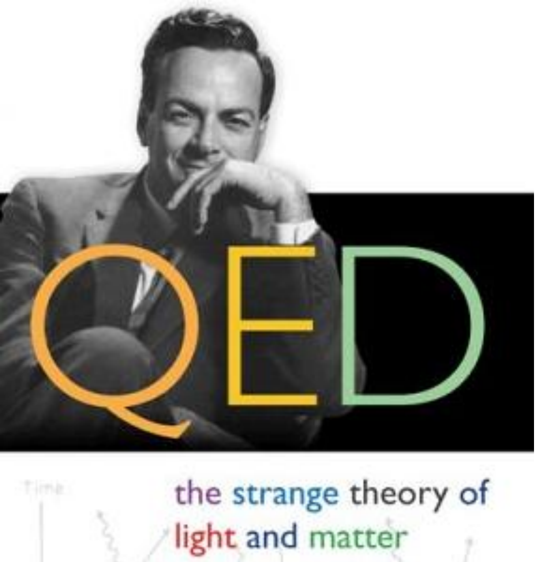


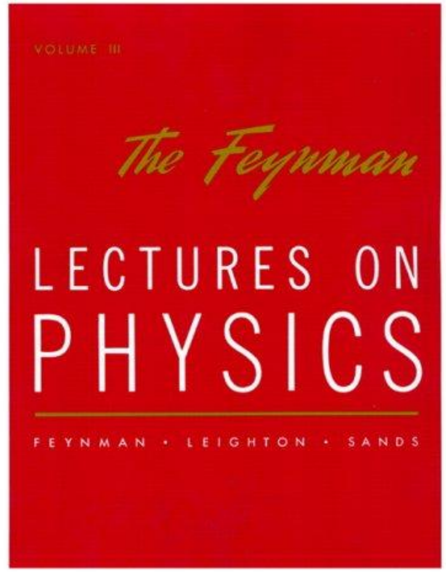


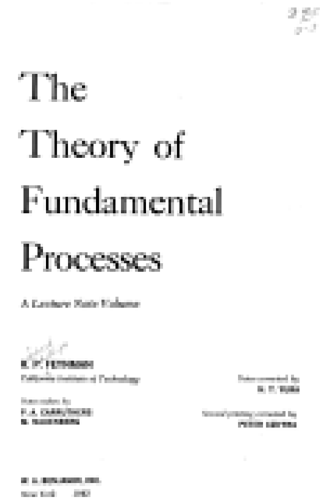


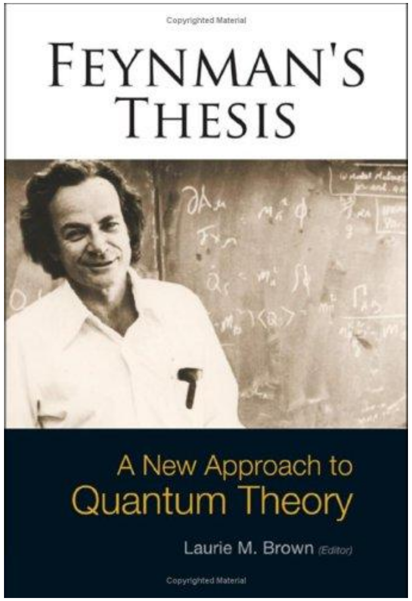


BOOKS BY FEYNMAN


QED
the strange theory of
light and matter


VOLUME III
The Feynman
LECTURES ON
PHYSICS
FEYNMAN · LEIGHTON · SANDS


The
Theory of
Fundamental
Processes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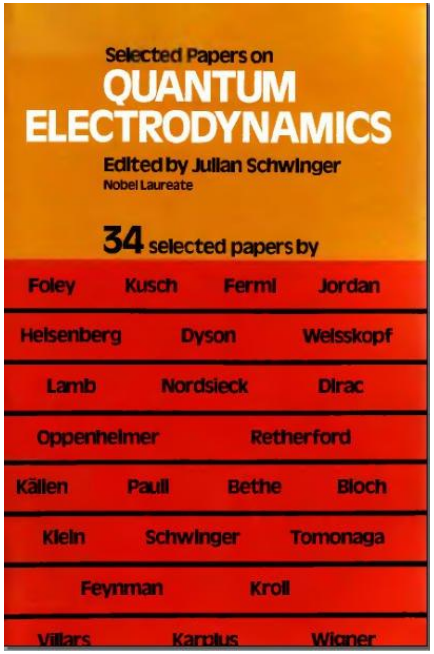
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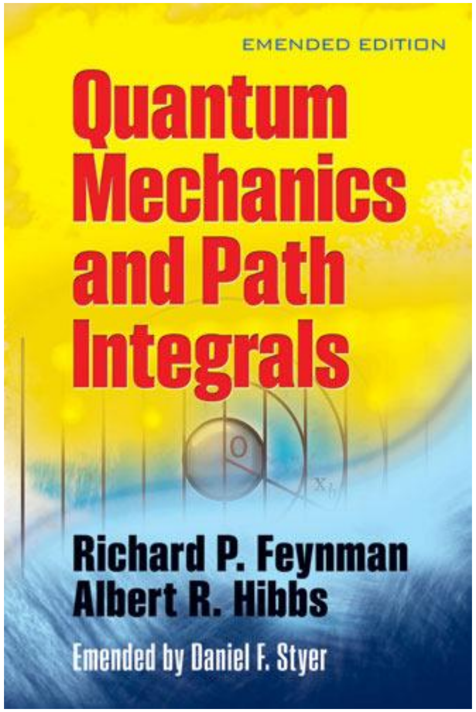
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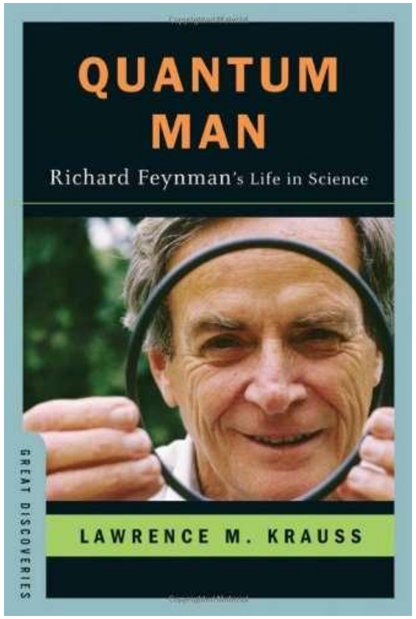
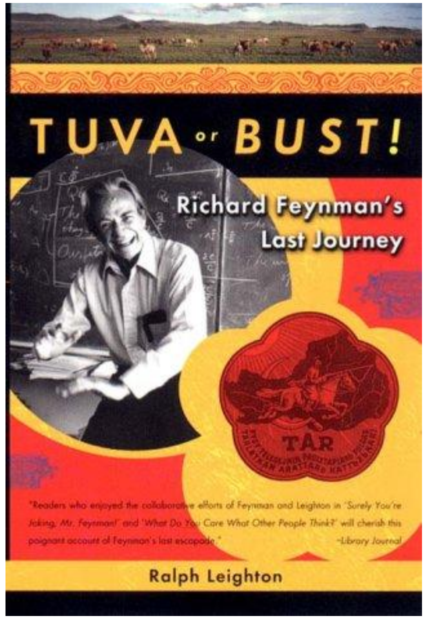
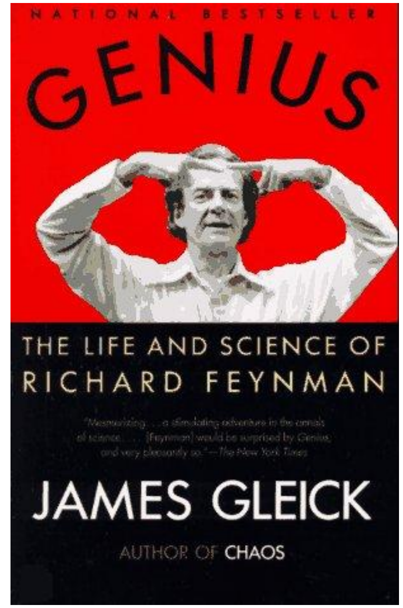
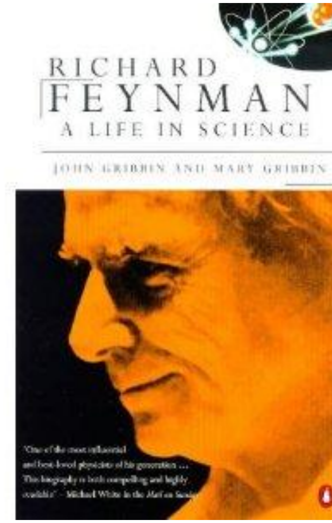
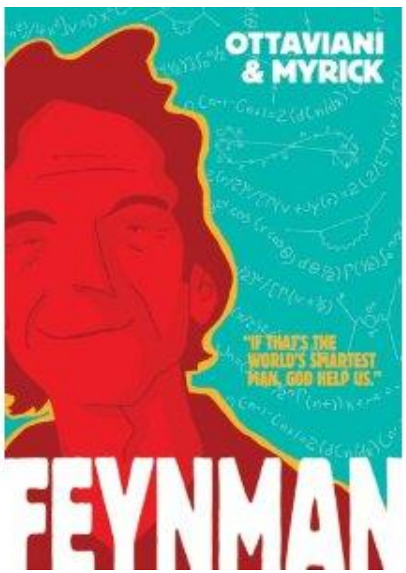
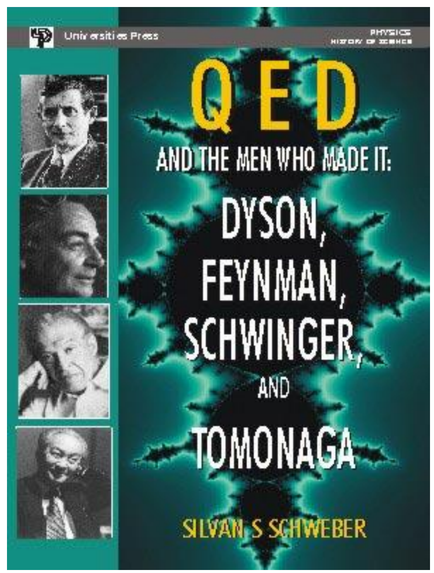


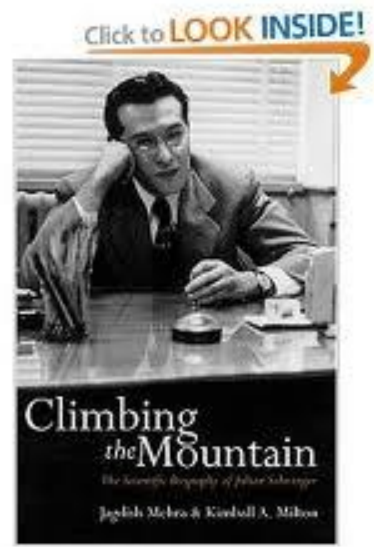












BOOKS ABOUT FEYNMAN

My Feynman Stories

- Feynman at Hughes
- Feynman and safes at Los Alamos
- Feynman at Aspen
- Dick O’Fey’s talks to UCI undergrads
- Feynman, Drell, Gell-Mann
- Talk on scheme of physics
- Negative Probabilities

Technical Appendices

Technical Appendix: The Action in Physics

- Difficult classical physics problems are solved by minimizing the "action" S which is defined as the sum (integral) over time, over a path, of the kinetic energy (K.E.) minus the potential energy (P.E.):

  $S = \sum (\text{K.E.} - \text{P.E.}) \Delta t$

- Traveling on a level surface with no P.E., for a car, say,

  $\text{S} = \text{K.E.} \cdot \text{time}$

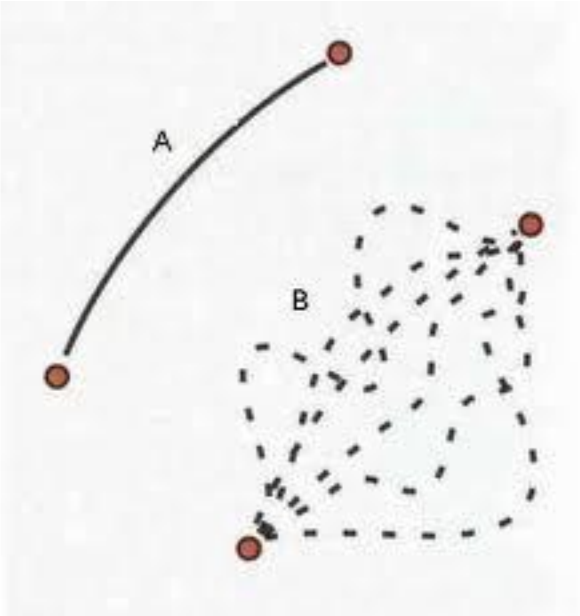
- So the principal of least action for a drive means minimizing the time it takes, something we intuitively do all the time.
- For QED, the action S includes includes the interaction of the electron current eJ with the electromagnetic field A:

  $eJ{\cdot}A$, where e is the charge of the electron.

Technical Appendix: The Sum over Paths, or Path Integral

- In Quantum Mechanics, a particle is also a wave, which travels over many paths.
- Feynman looked at QM by summing over all possible paths that a particle could take, allowing wavelike interference by using as a *phase* the action $S/\hbar$ on that path, in B. For those paths for which S is very near its minimum, they all have almost the same value of S, and they interfere constructively, thereby giving the classical path, and explaining the classical Principle of Least Action, which is equivalent to Newton's Law, but used for complex problems.

Classical Path



Quantum Paths

The Generation of Feynman Graphs in QED

- The action enters in an exponential function as a phase:
  $\exp(i S / \hbar)$.
- When the exp function is expanded it is a series in all powers in S, or all powers of the interaction vertex eJ·A.
- Thus all orders of photon exchange are included.
- Since each photon exchange has two currents, one at each end, it is a series in order of e^2 or $\alpha = e^2/\hbar c$. Since α is small it is called a perturbation series, and only a few terms are usually needed.
- A produced photon would have just one current eJ·A, and A would be the photon's outgoing wave function.

Technical Appendix: Removing the infinities

- The higher order diagrams in QED had mild infinities.
- Feynman first formulated a high energy cutoff, that could be due to unknown physics at very short distances.
- He then showed that some infinities could be cancelled, and others absorbed by replacing the bare or input masses and charges by their physical values.
- He published this in 1949.
- His colleague and friend Freeman Dyson showed that this could work to all orders.

Technical Appendix: Parton Math and Scaling

- With the proton having momentum p, the parton having momentum xp, and the photon having momentum q, the scattered parton has final momentum (xp + q).
- The condition that it be a free particle is $(q + x\,p)^2 = m^2$.
- Multiplying this out we have $q^2 + 2\,x\,p\cdot q + x^2\,p^2 = m^2$
- Now $p\cdot q = m\nu = m\,(E-E')$ (in the lab frame), where E is the incoming electron energy, and E' is the outgoing electron energy.
- At large q^2 and ν we ignore p^2 and m^2, giving
- $q^2 + 2xp\cdot q = 0$, or: $q^2 + 2\mathrm{x}m\nu = 0.$
- therefore, $x = -q^2/(2m\nu)$, the Bjorken or Feynman x!
- With k the incoming electron momentum, and k' the outgoing electron's ,
- $q^2 = (k - k')^2 = -2k\cdot k' = -2\,E\,E'\,(1 - \cos\theta)$ where θ is the electron scattering angle.
- Experiments summing over all hadron final states of the same x should have the same result, even for different values of q^2 and ν, as long as they give the same ratio x.
- This is called Feynman-Bjorken scaling.