Feynman's Path to Nobel ...

... and Beyond

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Road to Stockholm: Feynman's Nobel Lecture

Teaching Quantum Field Theory

Beyond Sweden: Mr Smith Goes to Chapel Hill

Road to Stockholm: Feynman's Nobel Lecture

A seventeen-year old Feynman entered MIT in1935. By the time he graduates in 1939, he is recognized as one of the most promising physics students of his generation.

By his junior year at MIT he had read Dirac's "Principles of Quantum Mechanics", and moved on to Dirac's formulation of quantum electrodynamics. There was a serious problem: calculations of physical quantities yielded infinite answers associated with the self-energy of the electron and the infinite number of degrees of freedom.

Young Feynman proposes an easy solution: the electron electromagnetic field does not act on itself! Why didn't anyone think of it? End of Story!

"Fell in love with this idea"

First paper Phys. Rev. 50, 340(1939), "Forces in Molecules" brought simplicity to a complicated problem:

"The force on a nucleus in an atomic system is shown to be just the classical electrostatic force that would be exerted on this nucleus by other nuclei and by the electrons' charge distribution."

Acknowledges John C. Slater and W. Conyers Herring[1]

[1]Conyers Herring, a solid state physicist and the 1984 Wolf Prize recipient for his work on energy levels in materials.

One of five 1939 Putnam Fellows in the second year of the William Lowell Putnam Mathematical Competition.

Glowingly recommended by J. C. Slater and (I assume) Conyers Herring, he entered Princeton Graduate School in Fall 1939.

Thus began Feynman's Journey to Stockholm

Feynman's *Modus Operandi* Put in Evidence

- Playing cat and mouse games with ideas
- Tenacity brushing off obstacles in his way
- Amazing ability to calculate
- Love of Calculation
- Reverence for Experiment
- Demanding Simplicity
- Intuition for the Right Answer

Feynman Nobel Lecture: must reading for Aspiring Physicists

First Obstacle in Graduate School

A radiating electron loses energy and that loss is reflected by the physical radiation resistance which had been shown to be related to self-energy.

Cannot ignore self-energy!

Feynman calculates in his version: shake a particle which sends a retarded signal to another which sends a signal back received later. There is a signal but it is mass dependent and comes later. Radiation resistance is instantaneous and independent of masses.

Feynman's idea is stupid on many grounds. His advisor Wheeler[2] admonishes

"Little Steps for Little Feet"

but ... this was Feynman and Wheeler asks, couldn't a shaken source emit both retarded and advanced signals?

Advanced signals had been discussed by Dirac (Proc. Royal Society (London) A167, 148(1939)) who showed the classical power divergence in the electron self-energy can be absorbed by a redefinition (renormalized) of its mass.

Feynman was in the habit of "reading" every paper in the Physical Review, meaning that he read the abstract and reconstructed the content.

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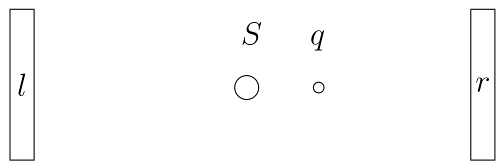
[2]When I asked Wheeler about this episode and remembered his remarks but added that the no-field hypothesis was his idea!

An Example of Feynman's Simplicity and Elegance of Thought

Consider a source S at the center of a wall of absorbers ten light-years away to its left and to its right, and position a test charge q one light-year to the right of the source



At $t = 0$ Feynman shakes the source, sending both retarded and advanced signals which hit the test charge at $t = +1$ and $t = -1$, respectively

- The source's retarded signal also hits both walls at $t = +10$

- The advanced signal from the left wall l hits the test charge at $t = -1$

- The advanced signal from the right wall r hits the test charge at $t = +1$

Feynman calculates the net effect felt by the test charge, assuming that advanced and retarded signals have the same strength

- the two signals received by the test charge at $t = -1$ cancel out

- the two signals received at $t = +1$ add up, and causality is restored

Feynman's dream is realized: No fields - Only Electrons

Electrodynamics is now written in terms of electrons with worldlines $x^i_\mu(\tau_i)$ interacting with one another "at-a-distance" through their currents,

$$\sum_i m\sqrt{\dot{x}^i_\mu(\tau_i)\dot{x}^i_\mu(\tau_i)} + \frac{1}{2}\sum_{i\neq j} e^2 \int \dot{x}^i_\mu(\tau_i)\dot{x}^j_\mu(\tau_j)\delta(s^2_{ij})d\tau_i d\tau_j$$

$s^2_{ij} = [x^i_\mu(\tau_i) - x^j_\mu(\tau_j)](x^i_\mu(\tau_i) - x^j_\mu(\tau_j]$ is the square of the invariant interval between two electrons.

Meet Feynman's first "propagator": $\Delta(x,y)_f = \delta[(x-y)^2]$

with conformally invariant boundary conditions. It will not be his last!

The fake electromagnetic potential at an arbitrary point z_μ is a construct

$$A_\mu(z_\mu) = \sum_i \int dx^i_\mu \delta\big[(z_\mu - x^i_\mu(\tau_i))(z_\mu - x^i_\mu(\tau_j))\big]d\tau_i$$

Adding the "Absorber Hypothesis" which posits that the sum total of the radiation from all the electrons in the world is absorbed, Feynman and Wheeler obtain a beautiful formulation of classical electrodynamics.

It was a strange formulation since the path of a particle at a given time depended on what had happened to it previously.

Feynman was at ease with it although disdainful of the Hamiltonian formalism where differential equations determine the system at any given time.

Feynman kept on playing, like replacing the delta function propagator by a highly peaked function with tiny width ...

Equally adept at using advanced and retarded signals, Wheeler thought of positrons as electrons going backwards in time, a crucial idea for Feynman's later development.

Quantum Mechanics Cannot Be Ignored

Feynman seeks a Lagrangian formulation of Quantum Mechanics

In September 1941, the german physicist Herbert Jehle, recently released from internment[3], arrives in Princeton where he meets Feynman over beers at the Nassau Inn.

[3]Son of a general, Jehle was a quaker who had refused military service and was interned at Camp Gurs in southern France by the Vichy government

During physics chit-chat, Feynman expresses frustration on his inability to describe Quantum Mechanics in terms of positions and velocities.

A little bit of luck never hurts because Jehle had been trying to make sense of a 1933 paper in which Dirac had introduced such a formulation, using sum over paths, with the classical path singled out as $\hbar \to 0$!

Dirac forever the purist, had not pursued an approach based solely on analogies

Feynman's antennae went up, and the very next day they found the paper in the Princeton library[4]

Days later, Jehle asked about Dirac's paper, and got a Feynmanesque answer

"Not only did I read it, I derived Schrödinger's equation from it"

Years later Feynman remembered Jehle's eyes seemingly bulging out like saucers!

"Damn the Torpedoes!"

Feynman had turned Dirac's analogy into reality

[4]To Jehle's congratulatory message for his Nobel Prize, Feynman responded *"Dear Dr Jehle, It is all because you showed me Dirac's article in the library at Princeton. Thank you very much"*

May 1942 Feynman presents his thesis

"The Principle of Least Action in Quantum Mechanics"

Uses sum over paths to derive the the non-relativistic Schrödinger's equation

Curiously no reference to Dirac's "The Lagrangian in Quantum Mechanics" nor to Jehle

Treats in some detail forced harmonic oscillators.

Assumes it can be carried to the Feynman-Wheeler action

No time to go any further ...

"got a kind of funny feeling that things were not exactly right"

December 1941 the United States enters the war

Feynman soon recruited by Bob Wilson for the Manhattan project.

Soon totally absorbed by war work, and his brilliance and importance became obvious:

Los Alamos National Laboratory (1945)

THEORETICAL DIVISION
MAY 10, 1945

H.A. Bethe, Division Leader, E-208, Ext 71
V.F. Weisskopf, Deputy Division Leader, E-217, Ext 74
J. von Neumann, Consultant, E-205 , Ext 72 R3

GROUP T-1
R. Peierls, E-119, Ext 178
R.F. Christy, Section Leader E-120, Ext 178 R2
K. Fuchs, Section Leader, E-118, Ext 77
Baroody, E.M., E-121, Ext 178 R2
Calkin, J.W., E-117, Ext 77
Inglis, D.R., T-35, Ext 54
Keller, J., E-120, Ext 178 R2
Penny, W.G., E-101A, Ext 470
Podgor, T/5 S., E-116, Ext 469
Roberts, T/5 A.E., E-117, Ext 77
Skyrme, T.H.R., E-118, Ext 77
Stark, R.H., E-116, Ext 469
Stein, T/5 P.R., E-121, Ext 178

GROUP T-2
R. Serber, Leader, E-109, Ext 177
L.I. Schiff, Alt. Leader, E-108, Ext 76
Case, K.M., E-107, Ext 76
Glauber, R., E-107, Ext 76
Kurath, T/3 D., E-202, Ext 205
Rarita, W., E-111, Ext 177
Richman, C., E-110, Ext 177
Stehle, T/5 P., E-107, Ext 76

GROUP T-3
V. Weisskopf, Leader, E-217, Ext 74
R.E. Marshak, Alt. Leader, E-218, Ext 74 R2
Bellman, Pvt. R., E-222, Ext 468
Cohen, T/5 S., E-219, Ext 74 R2
Lennox, T/5 E., E-218, Ext 74 R2
Olum, Paul, E-216, Ext 74
Smith, J.H,, E-219, Ext 74
Wing, Milton, E-222, Ext 468
Bowers, W.A., E-216, Ext 74

GROUP T-4
R. Feynman, Leader, E-206, Ext 72
J. Ashkin, E-209, Ext 72 R2
Ehrlich, R., E-210, Ext. 72 R2
Peshkin, T/4 N., E-203, Ext. 79 R3
Reines, F., E-210, Ext 72 R2
Welton, T.A., E-209, Ext 72 R2

GROUP T-5
D. Flanders, Leader, E-205, Ext 69 R1
P. Whitman, Alt. Leader, E-204, Ext 69 R2
Atkins, A.L., E-211, Ext 73 R2
Davis, R.R., E-215, Ext 74
de le Vin, E., E-201, Ext 79
Elliott, J., E-213, Ext 73 R1
Hauser, T/5 F.H., E-214,
Huber, T/4 .C., E-120, Ext 70
Hudson, H., E-214, Ext 73 R1
Inglis, B., E-212, Ext 73 R2
Johnson, M., E-212, Ext 73 R2
Kellogg, T/5 H., E-203, Ext 69 R3
Langer, B., E-201, Ext 79
Page, T/3 W., E-214, Ext 73 R1
Rau, E., T/3, E-120, Ext 70
Staley, T/3 J., E-212, Ext 73 R2
Teller, M., E-214, Ext 73 R1
Vuletic, T/5 V., E-211. Ext 73 R2
Wilson, F., E-212, Ext 73 R2
Wright, T/5 E., E-213, Ext 73 R1
Young, T/Sgt., G., E-211, Ext 73 R2

GROUP T-6
E. Nelson, Leader, E-116
N. Metropolis, Alt. Leader, E-115, Ext 78
R. Feynman, Consultant, E-206, Ext 72
Ewing, F.E., E-112, Ext 75
Goldberg, T/5., E-108, Ext 76
Kemeny, Pvt. J., E-105, Ext 75
Hamming, R.W., E-114, Ext 78
Heermans, Corp. A., E-105, Ext 75
Heller, T/5 A., E-105, Ext 75
Hurwitz, T/5 D., E-105, Ext 75
Johnston, T/3 J., E-103, Ext 75
Kington, T/4 J., E-105, Ext 75
Livesay, N., E-112, Ext 75
Ninger, H., E-105, Ext 75
Noah, F.E., E-105, Ext 75
Vorwald, T/5 A., E-105, Ext 75
Zimmerman, T/3 W., E-105, Ext 75

GROUP T-7
J. Hirschfelder, Leader, T-30, Ext 206
J. Magee, Alt. Leader, T-30, Ext 206
Brummer, T/5 E., T-28, Ext 206
Feckete, T/4 P., T-26, Ext 206
Larson, T/4 L., T-28, Ext 206
Ostrow, E., T-30, Ext 206
Schwartz, T/4 P., T-28, Ext 206

GROUP T-8
G. Placzek, Leader, E-220, Ext 468
Mark, C., E-221, Ext 468 R2
Carlson, B., E-221, Ext 468 R2
Day

In his Nobel lecture he hardly mention the war years

There was little time to work on developing his own physics ...

On long bus rides he sneaks a few calculations and realizes that his quantum mechanics applied to his cherished action yields complex energies.

Unitarity is violated- It does not work

War is Over

Hans Bethe recruits Feynman to Cornell in 1946

Time to Take Stock - Not everything is lost

Has a new way of doing quantum mechanics by relating amplitudes to paths

Tries his new quantum mechanical formalism to the four-component Dirac equation. Could not find four paths, but in two dimensions, the two components could be linked to left- and right-moving paths

Restless Feynman keeps playing, inventing little models, calculating ...

In 1947 W. Lamb and Retherford measure the tiny frequency shift between the $2S_{1/2}$ and $2P_{1/2}$ levels of Hydrogen of about 1000 Mhz.

Experiment!

Feynman is excited: finally a way to test the marriage between quantum mechanics and fields!

In Feynman's psyche lies an irresistible urge to explain this number!

Bethe thinks the infinity of the electron's self energy will cancel out in the difference of two energy levels. He proceeds to estimate the shift,

His expression is divergent but in a way that suggests a different culprit - the non-relativistic approximation.

Aside from infinities(!) Bethe gets the right order of magnitude for the Lamb shift!

Feynman calls Bethe's physics feat of arms

"the most important discovery in the history of quantum electrodynamics"

Bethe's estimate was full of ambiguities especially as to where the infinities were hiding in the calculation

Feynman and Bethe calculate the electron self-energy on the blackboard and get a nonsense (power) divergent answer!

Feynman decides to learn how to make a calculation!!!

Starts from scratch, using Dirac's electrodynamics with a retarded highly peaked propagator of width a

Makes up a whole set of rules as he goes along!

The Result

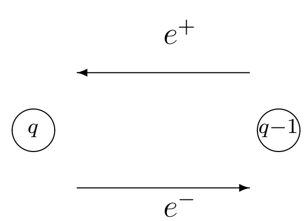
The correction to the mass is proportional to $\ln(ma/\hbar)$; the infinity reappears when $a \to 0$

After a Bethe tutorial, Feynman calculates the Lamb shift and finds the logarithm cancels out.

- Guesses the relativistic rules for the interaction with matter from the non-relativistic path integral method

- The major and most confusing step in the relativistic generalization was the inclusion of antiparticles.

Wheeler's old idea of positrons as electrons going backwards in time comes to the rescue.



New propagator required, Feynman's second and final propagator

"They call it Δ_F I don't know why"

Coulomb and radiation parts of the standard calculation automatically linked by Lorentz invariance. Sums over all four polarizations!

To organize the calculations he invents graphical rules[5]

"It's just perturbation theory plus logistics, and that's the hard part!"

One of Feynman's favorite textbook is *Statistical Mechanics* by Joseph Mayer and Maria Goeppert-Mayer (1940)

A graphical method to evaluate the partition function as sums over molecular clusters

Mayer-Mayer rules

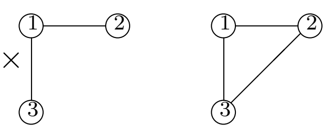
Circle: Molecule

Line between two circles denotes interaction:

$$f_{ij} = e^{-u(r_{ij})/kT} - 1, \quad f \sim r^{-3},\ r \to \infty$$

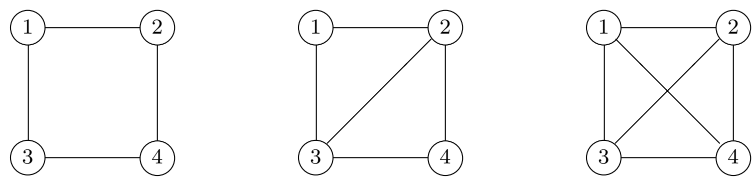
Three-Molecule Clusters:

3×



[5] Feynman told me that he remembered a Sunday morning in Ithaca when he was in his pyjamas on the floor drawing sheet after sheet of diagrams and wondering if these would be of any use!

Four-Molecule Irreducible Cluster:



Inspiration for Feynman Diagrams?

It is most striking that most of the ideas developed in the course of this research were not ultimately used in the final result

"the half-advanced and half-retarded potential was not finally used,

the (time symmetric) action expression was not used,

the idea that charges do not act on themselves was abandoned.

the path-integral formulation of quantum mechanics was useful for guessing at final expressions and at formulating the general theory of electrodynamics in new ways ? although, strictly it was not absolutely necessary.

... the idea of the positron being a backward moving electron ... was very convenient, but not strictly necessary ... because it is exactly equivalent to the negative energy sea point of view".

Feynman ends his Nobel lecture on a very personal note

So what happened to the old theory that I fell in love with as a youth? Well, I would say it's become an old lady ... and the young today will not have their hearts pound anymore when they look at her[6]*. But, we can say the best we can for any old woman, that she has been a very good mother and she has given birth to some very good children.*

[6]A much younger version of the author applied the Feynman approach to strings, leading to the ubiquitous antisymmetric second-rank tensor field

Feynman's 1978 Quantum Field Theory Course

Attended with Graham Ross on MWF 11 a.m.

Electrodynamics as example
Dirac Field as example
QED

Physically there is nothing divergent provided you ask the right question

What to do with divergent integrals? In general they are infinite

Gauge Invariance
Infrared Difficulties
Perturbation Theory
Renormalization

Scalar Field Theory

Gauge Theories

Classical (Lie groups)
Lagrangian
Hamiltonian
Hamiltonian in certain gauges

Quantum Theory

Quantum theory of any field is just the question of computing the amplitudes for finding a given shape

Path Integral Method
Fadeev-Popov ghosts
Survey of Weak Interactions - Weinberg-Salam model.
Classical Solutions of Yang-Mills Theories
Quark Confinement

All we know about confinement is the collapse of a proof that it does not confine

Topology Instantons - η' solution
Wilson's Criterion
Anomalies
Mach's Principle
Hidden Variables

We are better than mathematicians, we only say $1, 2, ..., \infty$

It is necessary that the students be better than the Professor in something - otherwise we are making no progress for the race

If it's dark it should be dark when you're running

Throw away the self-energy of the electron in a relativistic way- this is what took twenty years!

It's the Goddam harmonic oscillator again!

Quark Masses and Mixings

"Injected in the theory by hypodermic needle"

"You want more than a Nobel Prize? You want to become a king? Figure that out!"

Beyond Sweden: Mr Smith Goes to Chapel Hill

In January 1957 Bryce DeWitt and Cécile DeWitt-Morette organized the inaugural conference of the "Institute Of Field Physics" created by Agnew Bahnson at the University of North Carolina

The Role of Gravitation in Physics

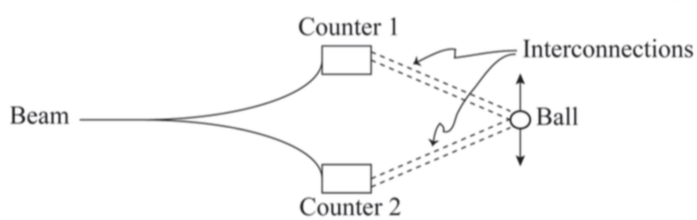
Skeptical Feynman registered as "Smith" but said

"The problem of the relation of gravitation to the rest of physics is one of the outstanding theoretical problems of our age"

Does Gravity Need to be Quantized?

Feynman's Gedanken experiment

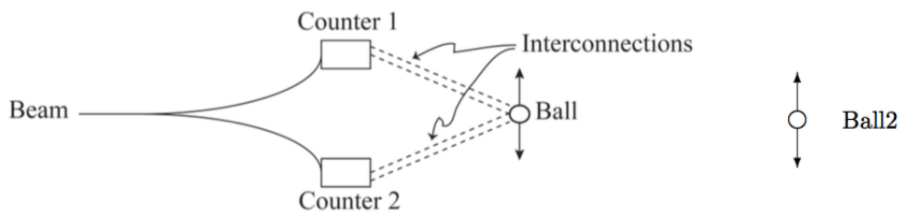
Stern-Gerlach experiment with rods connected to macroscopic ball (1 cm)



Ball (Schrödinger's cat) moves up or down depending on spin

- Complex amplitudes for ball up and ball down
- Possible Interference (unless measured)
- Reversible

Add a second ball



Gravitational field of the connected ball is real and big enough to affect the second ball (Ball2)

Use the second ball as measuring device

Two complex amplitudes for ball2 motions

A new link in the measurement chain

Link must involve amplitudes

Gravitational Radiation

Link is reversible[7]

"If you believe in quantum mechanics up to any level you have to believe in gravitational quantization to describe this experiment"

[7] *"Otherwise a new principle: Any piece of equipment able to amplify by such and such a factor (10^{-5} grams or whatever it is) necessarily must be of such a nature that it is irreversible"*

Feynman's Guide to Gravitational Research

- understand classical relativistic gravity without the complications of other things
- general theory of cosmology may be able to work out the shape of the world
- study the theory to see if anything new is in it which is not contained at first sight
- learn from the philosophy of gravity something to use in other fields
- curiosity

Two ways to deal with problems where no experiments are available

- Apply Mathematical Rigor

- Play Games

Best is to pretend there are experiments and calculate

"... since we are not pushed by experiments we must be pushed by imagination"

" The real challenge is not to find an elegant formalism
but to solve a series of problems whose results could be checked"

"Don't be so rigorous or you will not succeed"

Gravity: Beautiful theory unchallenged by experiment

Rest of Physics awash in experiments but without a beautiful theory

Suppose Einstein never existed ...

Invent New Field

Massless with spin two $h_{\mu\nu}$ coupled to current $T_{\mu\nu} = \int \dot{z}_\mu \dot{z}_\nu \delta^4(x-z)dS$

Equation of motion: $g_{\mu\nu}\ddot{z}_\lambda = [\mu\nu, \lambda]\dot{z}_\mu \dot{z}_\nu$

In electrodynamics current conservation is an identity from field equations

Not true for $T_{\mu\nu}$ Need to add something more

Look for cubic term in the action such that $g_{\mu\lambda}T_{\lambda\mu,\nu} = [\mu\nu, \lambda]T_{\mu\lambda}$

Begin an expansion. Ask a mathematician ...

Geometric Interpretation comes out of the wash

Use Old Physics

Neutrino exchanges do not give rise to $1/r^2$ law ... not a good idea!

Gravitational Radiation

Confusion about on the reality of the gravitational wave solution

Even Einstein was confused and Rosen even thought the solution was singular and carried no energy, but it was just a coordinate singularity:

Felix Pirani had showed just before the conference that gravitational waves are real by working out an invariant definition of Gravitational Radiation in terms of the Riemann Tensor

At Chapel Hill Pirani presents:

Measurement of Classical Gravitation Fields

"Measuring the relative acceleration of neighboring free particles yields information about the Riemann tensor"

$$\frac{\partial \eta^a}{\partial \tau^2} + R^a_{0b0}\eta^b = 0, \quad (a, b = 1, 2, 3)$$

"One can very easily imagine an experiment for measuring the physical components of the Riemann tensor"

Enter Feynman

"If they transport energy we can detect them"

Proposes the "sticky beads" experiment

Bead A is fastened to a rod

Bead B free to move along the rod

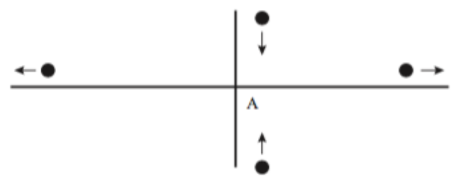
- A gravitational wave (discontinuity in the Rieman tensor) passes through

- A and B jiggle

- B rubs against the rod and loses energy by friction

Can gravitational waves be generated?

Gravitational waves generate quadrupole moment:



"My instinct is that a device which could draw energy out of a wave acting on it, must if driven in the corresponding motion be able to create waves of the same kind"

- *If energy is absorbed the wave must be getting weaker*

- *"How does it get weaker? The absorber generates the same wave which interferes with the original wave in the forward scattering direction, thus reducing the intensity for a subsequent absorber"*

"...these waves can be generated and are in every respect real"

The End