Quantum Electrodynamics (QED)

(*Listen, buddy, if I could tell you in a minute what I did, it wouldn't be worth the Nobel Prize* – R P Feynman)

Quantum electrodynamics is the theory that explains the interactions between light and matter. It is absolutely fundamental to our understanding of the world around us, explaining *everything* except gravity and nuclear reactions.

It was first formulated in about 1929, but it was riddled with problems, since whenever you tried to calculate something, the answer looked OK at first, before blowing up to infinity as the calculation progressed.

By 1948 Feynman straightened out QED, and resolved the meaningless results that the old quantum theory sometimes produced. Two other physicists, Sin-Itiro Tomonaga and Julian Schwinger, also came up with a patch for the theory independently of Feynman, but their solutions were not as imaginative, revolutionary, or far-reaching. All three received Nobel prizes in Physics for their work in this field in 1965.

$$\left[c\mathbf{a}\left(-i\ \nabla-\frac{e}{c}\mathbf{A}\right)+bmc^2\right]\psi=\left(i\ \frac{\partial}{\partial t}-e\phi\right)\varphi$$

$$\nabla^2\mathbf{A}-\frac{1}{c^2}\frac{\partial^2\mathbf{A}}{\partial t^2}=-4e\varphi'\mathbf{a}\varphi$$

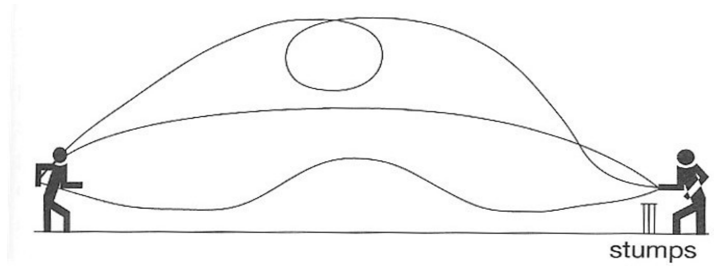
$$\frac{1}{\ }\ \frac{\partial^2\phi}{\ }$$

Thirty-one years ago Dick Feynman told me about his 'sum over histories' version of quantum mechanics. "The electron does what it likes," he said. "It just goes in any direction at any speed, however it likes." I said to him, "You're crazy." But he wasn't.

Freeman Dyson

In Feynman's formulation of QED, all paths that a particular particle could follow are considered. Each path contributes an amplitude to the final answer which is the most likely path.

For example, light doesn't have to travel in a straight line – in Feynman's system, all paths for a photon are considered! It turns out, when you do the maths, all the really long paths have low amplitudes, so the straight line turns out to be the most likely path.



Possible paths for a cricket ball

In the situation above, the unusual paths have tiny amplitudes, whereas paths close to the 'correct' one have large amplitudes, and hence large probabilities. It turns out that the actual path followed is the path of least action.

Feynman himself described his theory as "dippy" and it certainly isn't intuitive, but it does work fantastically well. He also introduced simple diagrams, now called Feynman diagrams, which enabled him to represent visually the complicated mathematical expressions needed to describe the behaviour of systems of interacting particles. Feynman diagrams allow difficult concepts to be made much more approachable.

Feynman's Other Important Contributions

Superfluidity

In the early 1950s Feynman provided a quantum-mechanical explanation for the Soviet physicist Lev D. Landau's theory of superfluidity

Superfluidity is the strange, frictionless behaviour of liquid helium at temperatures near absolute zero, where helium seems to display a lack of viscosity when flowing. It is therefore able to flow with no difficulty through extremely small holes, which ordinary liquid helium cannot do.

On the walls of its container, superfluid helium forms a thin film (approximately 100 atoms thick) that flows against gravity up and over the rim of the container, emptying it. Once a flow is started in the superfluid, it carries on indefinitely.

By applying the Schrödinger equation from quantum mechanics to the question, Feynman showed that the superfluid was displaying quantum mechanical behaviour observable on a macroscopic scale. This later helped enormously with the problem of superconductivity.

Weak Force

In 1958, Feynman collaborated with another American physicist, Murray Gell-Mann, to devise a theory that accounted for most of the phenomena associated with the weak force.

This is the force responsible for radioactive decay, and is one of the four fundamental forces of nature. An example of weak decay is the decay of a neutron into an electron, a proton, and an anti-neutrino.

Their theory, which turns on a special property of particles called “spin” (it’s a bit like being left- or right- handed) has proved particularly fruitful in modern particle physics.

Although E.C. George Sudharsan and Robert Marshak developed the theory nearly simultaneously, Feynman's collaboration with Murray Gell-Mann proved to yield the better theory, which was of massive importance, and the weak interaction was neatly described.

Partons (Quarks)

In 1968, while working with experimenters at the Stanford Linear Accelerator, Feynman invented a theory of ‘partons,’ hypothetical hard particles inside the nucleus of the atom, to explain the results of experiments in which electrons were being slammed into protons.

When this happened, the low-energy electrons were just deflected a little, but high-energy electrons were scattered through a greater angle, producing a shower of exotic particles. This was the first evidence for the existence of charged particles inside protons and neutrons.

Feynman suggested that low-energy electrons could not ‘see’ the different charges inside the proton – the charge appears to be smeared out – but high energy electrons could, interacting with the individual charges. Just as you could see individual rotor blades on a helicopter if you moved fast enough.

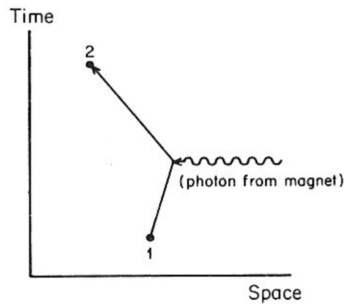
Although the results were explained by Murray Gell-Mann’s equivalent theory, involving quarks rather than using Feynman’s ‘partons’, Feynman’s insight offered an easier visual picture to grasp the interactions.

Putting QED 'through the wringer'

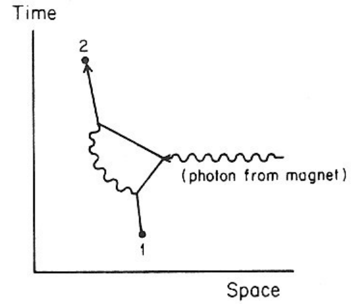
The theory of Quantum Electrodynamics is the best theory we have in physics today. It is phenomenally accurate in its agreement with experiment. It has lasted for more than fifty years, with no significant difference from experiment! We always try to test our theories of physics to the limit: Feynman said "That's the game, because if there *is* something the matter [with the theory], it's interesting!" But so far, we have found nothing wrong with QED. It is the jewel in the crown of physics – our proudest possession.

We shall consider just one value with which QED has been tested, a number which represents the response of an electron to an external magnetic field – something called the "magnetic moment." When Dirac first calculated this number, using his equations, he got the answer 1. It was later discovered that the actual value was closer to 1.00118, and this correction was expected, as physicists knew that Dirac's equations did not fully take into account electrons' interactions with light. Schwinger was the first to calculate a value for this quantity, and he got 1.00116, showing that he was on the right track.

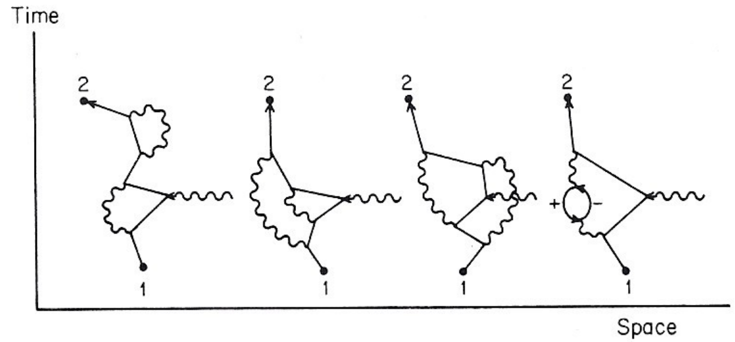
In QED, we calculate values using a mathematical approach known as the Feynman calculus. It turns out that the value we want can be calculated in a series of steps which assign contributions to each of the types of Feynman diagrams associated with the force, just like the sum over histories mentioned before. The more accurate we want the result, the more possible Feynman diagrams we draw, and include in our calculations.



Dirac's calculation only included this first diagram



Here is Schwinger's initial correction



Laboratory experiments became so accurate that further alternatives had to be calculated, some of which are shown here

Various teams are always improving the experimental values. The next contribution to the amplitude involves something like 70 diagrams. As of 1983, the theoretical number was 1.00115965246, and the experimental number was 1.00115965221. This accuracy is equivalent to measuring the distance from Los Angeles to New York, a distance of over 3000 miles, to within the width of a human hair. These numbers are meant to intimidate you into believing that the theory is probably not too far off!