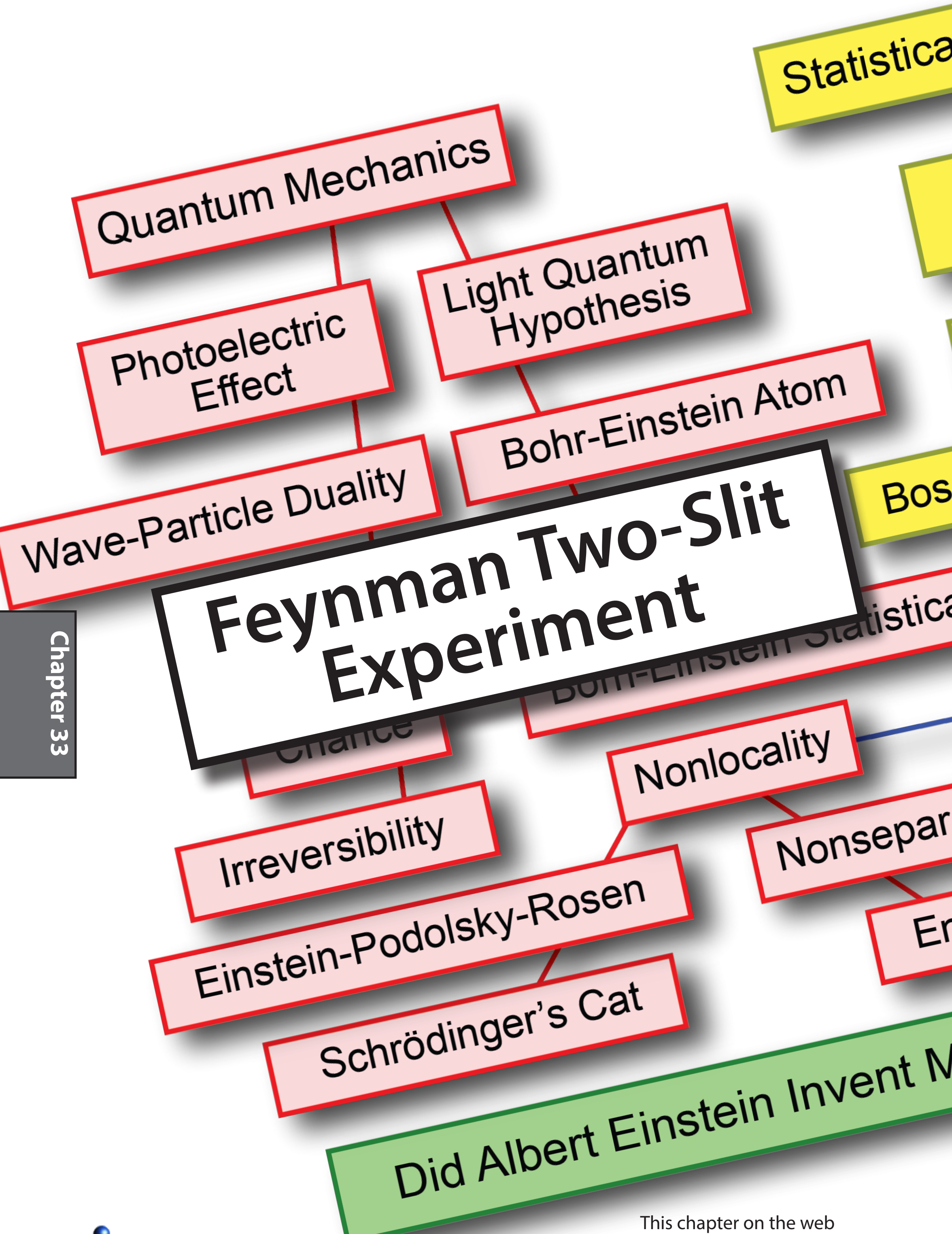
Chapter 33

Feynman Two-Slit Experiment



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Feynman Two-Slit Experiment

Richard Feynman said that the two-slit experiment contains "all of the mystery" of quantum mechanics.

> I will take just this one experiment, which has been designed to contain all of the mystery of quantum mechanics, to put you up against the paradoxes and mysteries and peculiarities of nature one hundred per cent. Any other situation in quantum mechanics, it turns out, can always be explained by saying, 'You remember the case of the experiment with the two holes? It's the same thing' I am going to tell you about the experiment with the two holes. It does contain the general mystery; I am avoiding nothing; I am baring nature in her most elegant and difficult form. [1]

We will show that the two-slit experiment does contain the key mystery of quantum mechanics, but it's not exactly what Feynman described in 1964. It is connected to the new mystery of "entanglement." Feynman's mystery was simply how a particle can interfere with itself if it goes through only one slit. Our view is that the particle goes through one slit. We show that it is the probability amplitude of the wave function that is interfering with itself.

We are making use of Einstein's vision of an "objective reality." We say the motion of an individual particle of matter or energy obeys fundamental conservation principles - conservation of all a particle's properties. This means the particle path exists and it is smooth and continuous in space and time, even if it impossible to measure the path, to determine its position without disturbing it.

This claim is very controversial, because Werner Heisenberg's description of the Copenhagen Interpretation insists that "the path only comes into existence when we measure it."

Einstein said that claiming a particle has no position just before we measure it is like saying the moon only exists when we are looking at it! That it is impossible *to know* the path of a particle without measuring it does not mean that a path does not exist.

1 Feynman, 1967, chapter 6

We are left with the mystery as to how mere "probabilities" can influence (statistically control) the positions of material particles - how *immaterial* information can affect the *material* world. This remains the deep *metaphysical* mystery in quantum mechanics.

There is something similar in quantum entanglement, where measurement of one particle appears to transmit something to the other "entangled" particle. In the two-slit experiment it is the value of the wave function at one place "influencing" the location where the particle appears. In entanglement, the collapse of the two-particle wave function leaves the spin components ot the two particles correlated perfectly.

Like Einstein's 1927 description of nonlocality, both of these involve the "impossible" simultaneity of events in a spacelike separation.

In the two-slit experiment, just as in the Dirac Three Polarizers experiment,[2] the critical case to consider is just one photon or electron at a time in the experiment.

With one particle at a time (whether photon or electron), the quantum object is mistakenly described as interfering with itself, when interference is never seen in a single event. It only shows up in the statistics of large numbers of experiments. Indeed, interference fringes are visible even in the one-slit case, although this is rarely described in the context of the quantum mysteries.

It is the fundamental relation between a particle and the associated wave that controls its probable locations that raises the "local reality" question first seen in 1905 and described in 1909 by Einstein. Thirty years later, the EPR paper and Erwin Schrödinger's insights into the wave function of two entangled particles, first convinced a few physicists that there was a deep problem .

It was not for another seventeen years that David Bohm suggested an experimental test of EPR and thirty years before John Stewart Bell in 1964 imagined an "inequality" that could confirm or deny quantum mechanics. Ironically, the goal of Bell's "theorem" was to invalidate the non-intuitive aspects of quantum mechanics and restore Einstein's hope for a more deterministic picture of an "objective reality" at, or perhaps even underlying below, the microscopic level of quantum physics.

2 See chapter 19.

At about the same time, in his famous *Lectures on Physics* at Cal Tech and the Messenger Lectures at Cornell, Feynman described the two-slit experiment as demonstrating what has since been described as the "only mystery" of quantum mechanics.

How, Feynman asked, can the particle go through both slits? We will see that if anything goes through both slits it is only *immaterial information* - the probability amplitude wave function. The particle itself always goes through just one slit. A particle cannot be divided and in two places at the same time. It is the probability amplitude wave function that interferes with itself.

A highly localized particle can not be identified as the wave widely distributed in space. We will show that the wave function is determined by the boundary conditions of the measuring apparatus. It has nothing to do with whether or not a particle is in the apparatus, though it depends on the wavelength of the particle.

The immaterial wave function exerts a causal influence over the particles, one that we can justifiably call "mysterious." It results in the statistics of many experiments agreeing with the quantum mechanical predictions with increasing accuracy as we increase the number of identical experiments.

It is this "influence," no ordinary "force," that is at the heart of Feynman's "mystery" in quantum mechanics.

We will show that the probability of finding particles at different places in the two-slit experiment is determined by solving the Schrödinger equation for its eigenvalues and eigenfunctions (wave functions and probability amplitudes), given the boundary conditions of the experiment.

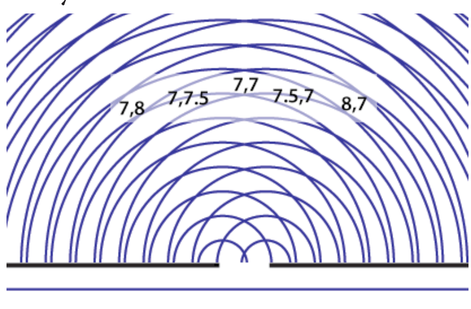
The wave function and its probabilities depend on the boundary conditions, such as *whether one slit is open or two*. They do not depend on whether a particle is actually present, though the calculations depend on the wavelength of a particle.

The two-slit experiment shows better than any other experiment that a quantum wave function is a probability amplitude that *interferes with itself*, producing some places where the probability (the square of the absolute value of the complex probability amplitude) of finding a quantum particle is actually zero.

Perhaps the most non-intuitive aspect of the two-slit experiment is this. When we see the pattern of light on the screen with just one slit open, then open the second slit - admitting more light into the experiment - we observe that some places on the screen where there was visible light, have now gone dark! And this happens even when we are admitting only one particle of light at a time.

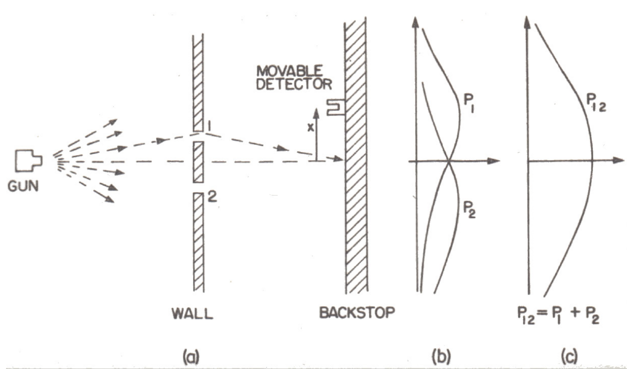
Let's remind ourselves about how the crests and troughs of water waves interfere, and then how Feynman presented the two-slit experiment to students in his famous *Lectures on Physics*.

Let's look first at the one-slit case. We prepare a slit that is about the same size as the wavelength of the light in order to see the interference of waves most clearly. Parallel waves from a distant source fall on the slit from below. The diagram shows how the wave from the left edge of the slit interferes with the one from the right edge. If the slit width is d and the photon wavelength is λ, at an angle $\alpha \approx \lambda/2d$ there will be destructive interference.

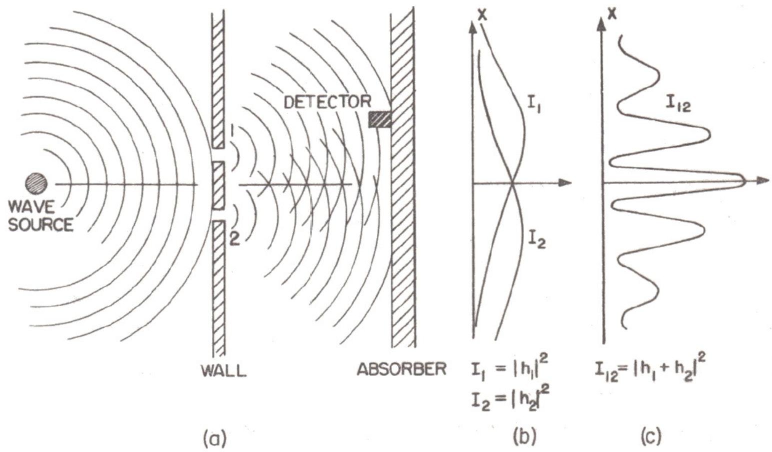


At an angle $\alpha \approx \lambda/d$, there is constructive interference (which shows up as the fanning out of light areas in the interfering waves in the illustration). The diagram indicates constructive interference between the 7th and 8th waves from the left and right sides of the slit.

Feynman began with a description of bullets fired at a screen with two holes, arguing that bullets do not interfere, he showed that the pattern with two holes open is simply the sum of the results from one hole or the other hole open. $P_{12} = P_1 + P_2$

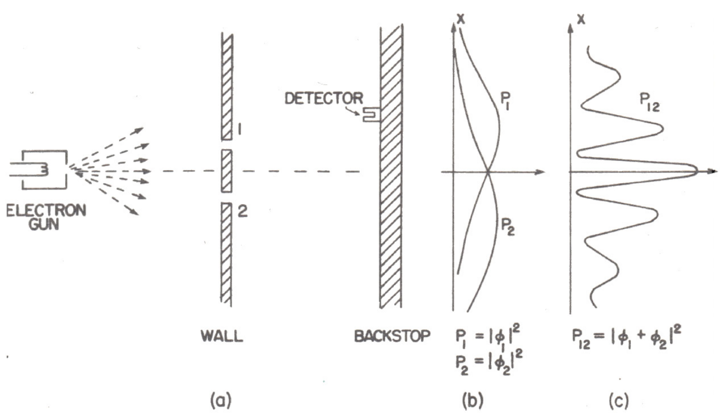


He then described the results for water waves.



Here the individual results I_1 and I_2 for one or the other hole open do not simply add up. The individual wave intensities are the squares of the amplitudes - $I_1 = |h_1|^2$, $I_2 = |h_2|^2$. Instead they show the cancellation of crests and troughs that produce constructive and destructive interference. The formula is $I_{12} = |h_1 + h2|^2$. This has the same pattern of bright and dark areas that are found in the "fringes" of light at the sharp edges of an object.

Feynman next shows how a two-slit experiment using electrons does not behave like bullets, but instead looks just like water waves, or light waves. He then shows that the mathematics is the same as for water waves. But he says "It is all quite mysterious. And the more



you look at it the more mysterious it seems." "How can such an interference come about?", he asks. "Perhaps...it is not true that the lumps go either through hole 1 or hole 2." He says

> We conclude the following: The electrons arrive in lumps, like particles, and the probability of arrival of these lumps is distributed like the distribution of intensity of a wave. It is in this sense that an electron behaves "sometimes like a particle and sometimes like a wave"...
>
> The only answer that can be given is that we have found from experiment that there is a certain special way that we have to think in order that we do not get into inconsistencies. What we must say (to avoid making wrong predictions) is the following.
>
> If one looks at the holes or, more accurately, if one has a piece of apparatus which is capable of determining whether the electrons go through hole 1 or hole 2, then one can say that it goes either through hole 1 or hole 2. But, when one does not try to tell which way the electron goes, when there is nothing in the experiment to disturb the electrons, then one may not say that an electron goes either through hole 1 or hole 2. If one does say that, and starts to make any deductions from the statement, he will make errors in the analysis. This is the logical tightrope on which we must walk if we wish to describe nature successfully.

Einstein was deeply bothered by this Copenhagen thinking that claims that we cannot know the particle path, that a path does not even exist until we make a measurement, that the particle may be in more than one place at the same time, maybe dividing and going through both slits, etc.

So let's combine *conservation principles* with Einstein's view that it is the wave function that determines the probability and the statistics of particle positions for a large number of experiments (he called it an "ensemble").

We can then argue, corresponding to Einstein's idea of an "objective reality," that the particle of matter or energy always *goes through just one slit* in a continuous, though *unknown* path.

But whichever slit the particle enters, the probability of finding it at a specific location inside the apparatus is determined by the square of the absolute value $|\Psi|^2$ of the complex probability amplitude at that location.

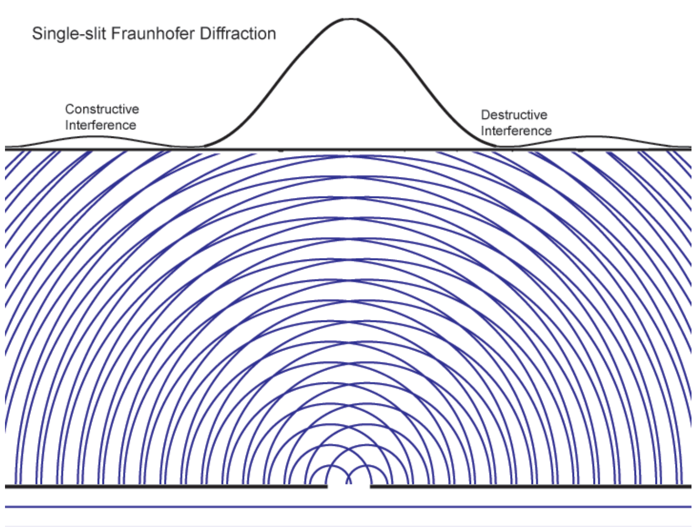
The probability amplitude is the solution to the Schrödinger equation given the boundary conditions. And the boundary conditions depend on whether one or two slits are open!

We can thus overcome Feynman's difficulties, his inconsistencies, his "special way to think," and his "logical tightrope." Mostly, Einstein's reality view denies an electron behaves "sometimes like a particle and sometimes like a wave." The particle is real. The wave is an accurate theory about the particle's behavior.

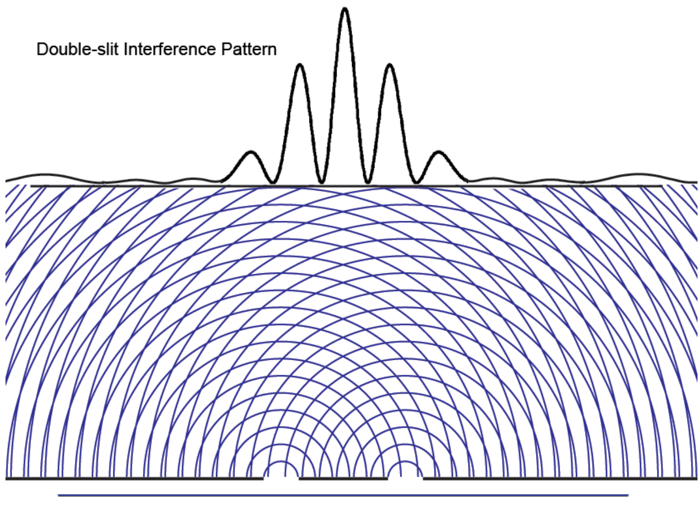
We may never be able to measure the specific location of an electron in an atomic orbit. But the wave function gives us all the information we need about atomic orbitals to do the quantum mechanics of atoms and possible molecules, with their nodal surfaces, just like the nodes in the two-slit interference pattern.

Let's compare the wave functions inside the two-slit apparatus when one slit or two slits are open.

With one slit open we see the classic Fraunhofer pattern with their light zones of constructive interference and dark zones where the waves are one-half wavelength different, so the crest of one wave cancels the trough of the other. Many texts mistakenly say that interference is only possible with two slits open.



With two slits open we can still see the overall shape of the single-slit Fraunhofer pattern with its broad central maximum, but now



multiple interference fringes appear.

We claim that this interference pattern *does not depend on which slit the particle enters*, but only on the probability amplitude of the wave function that solves the Schrödinger equation inside the experimental apparatus, given the boundary conditions, viz., which slits are open.[3]

While this picture eliminates the question of which slit the particle enters, it does not eliminate the deeper *metaphysical* mystery of how the *immaterial* information in the wave function can influence the particle paths and positions, one particle at a time, to produce the distribution of particles observed in the statistics of large numbers of particles.

But Einstein always said quantum mechanics is a statistical theory. And he was first to say very clearly that the waves, later the wave functions, are *guiding* the particles. He said the waves are a *guiding field* - a *Führungsfeld*.

It is this mystery, how abstract information can control concrete objects, not Feynman's worry about how a single particle can go through both slits, that is the deepest mystery in quantum mechanics.

3 David Bohm had a similar view. See chapter 30.

Feynman’s Path-Integral Formulation of Quantum Mechanics

In 1948 Feynman developed his “sum over paths” approach to quantum mechanics. It was based on a 1933 article by P. A. M. Dirac to formulate quantum mechanics using a Lagrangian function rather than the standard Hamiltonian, and to use a variational method to solve for the least action. It involves calculations over all space.

The idea of a single path for a quantum system (for example, the path of an electron or photon in the two-slit experiment) is replaced with a sum over an infinity of quantum-mechanically possible paths to compute the probability amplitude. The path-integral method is equivalent to the other formalisms of quantum mechanics but its visualization shows how it can sense when both slits are open.

Feynman’s calculation of the probability amplitude for a particle entering say the left slit, and arriving at a specific point on the detector screen, is the result of adding together contributions from all possible paths in configuration space, however strange the paths.

Each path contributes a function of the time integral of the Lagrangian along the path. In Feynman’s approach and in the transaction interpretations of quantum mechanics by John Cramer and Ruth Kastner, some paths explore the open slits.

The resulting probability amplitude is different at the back screen when one or both slits are open, just as we see in Einstein’s “objective reality” way of analyzing the problem.

In order for the state of the slits to “influence” the motion of each individual particle to produce the statistical interference pattern that shows up for many particles, the wave function has to “know” its value at every point inside the two-slit experiment.