An Easy Intro to Feynman's QED,
Part 2: Adding Alternative Histories (Transcript)
(Auto-transcript, no slides, no links, only mildly edited)

Terry Bollinger
May 16, 2026

Citation:

T. Bollinger, *An Easy Intro to Feynman's QED, Part 2: Adding Alternative Histories*. Apabistia Notes **2026**, 05161200 [May 16] (2026).

Slides: https://sarxiv.org/apa.2026-05-16.1200.01.pdf
Video: https://youtu.be/jNvkZKT9No4
Transcript: https://sarxiv.org/apa.2026-05-16.1200.02.pdf
Cite: https://sarxiv.org/apa.2026-05-16.1200.03.pdf

TB = Terry Bollinger
HM = Helen Ma (Team OrionX)
RS = Ron Schreiner
CP = Caetano Peng
RB = Robert E. Becker

Note: All timestamps below are 2 seconds ahead of video

0:02 HM Terry, let's start.

0:04 TB This is the second part of my series on
0:08 trying to repeat and introduce to people who may not be familiar with it some of the materials from Feynman's superb little book called QED, The Strange Theory of Light and Matter.
0:19 If you've never read the book, I really do encourage it. The original videos, which roughly follow the book and were done in New Zealand several years earlier.
0:29 are also available if you scrounge around for them online. A little bit, a little bit hard to find. I've got links to them in various places.
0:36 So, probably more than any other book I'm aware of.
0:43 Feynman's QED gives an explanation of some of the deepest physics in quantum theory, and does it in a way that uses only graphics, simple concepts of topology.
0:56 He points out where the math comes in, but his point is that the concepts underlying that math
1:02 Really are straightforward, and often very intuitive.
1:06 just to three-dimensional thinking. You can go through these issues surprisingly easily.

1:12 So, it’s an excellent book. He had an intentional goal of avoiding math, but still giving an accurate, correct description of theory for which he won a Nobel Prize. So, pretty remarkable combination, nice book.

1:25 has Feynman’s humor in it, and Feynman’s humor is always delightful. He has a sharp wit, and tends to know how to put a point forward in a nicely straightforward fashion.

1:38 So, I’ve got a lot to cover on this one. There’s a lot of material in the book, and I’m trying to give at least a quick dose of everything that he covers, because he covers so many marvelous little insights, like in this set of slides that I’m covering today.

1:53 There’s things about, how do photons figure out the shortest path to something? That’s not easy to do for us humans. We tend to mess up on that.

2:01 Why do lasers go in straight lines? Why do photons not go in straight lines? Which they don’t. Individual photons do not do that.

2:09 Focusing lenses, how do those work? Double slut experiment, diffraction gratings. All of these things, Feynman covers with remarkable conciseness in a fairly short amount of time using, a very simple set of graphical techniques. So, fascinating book for that reason.

2:30 quick review of what I said last time, because those concepts certainly play into what I’m talking about here.

2:37 The… if you don’t know who Feynman was, he’s just a delightful person to research a little bit.

2:49 Very sharp on his insights. Very, very careful, and this is something that I think is the reason I like Feynman’s work better than almost any other physicist that I’ve read.

3:01 With the possible exception of Einstein. Feynman would always, always, say, what does experiment say?

3:12 And one of the things that’s very common for many physicists is this temptation to go down the line saying, you know, I think it’s got to be this principle is what’s guiding everything. And then they’ll quote some principle from mathematics, they’ll quote some principle from a personal philosophy.

3:29 They’ll quote some reason why they think everything should work in such and such of a fashion.

3:34 Now, Feynman’s not adverse to doing that. I mean, obviously, he set up an entire framework in this, but there’s a humility which is in contrast to his overt personality, but it’s a humility about his own ideas.

3:47 that he just never accepted the idea that whatever he thought of first was correct. He would always look at it and say, is that right?

3:56 And is there something to tell me that it’s not right?

3:59 And this is a surprisingly rare kind of a precept for many people who go into physics theory.

4:08 It is very common to hear people say that, you know, this has got to be it, this is the explanation for everything, and go on and on with that.

4:16 Feynman also makes claims about QED. He says that it’s a powerful theory, it explains most of the regular world.

4:22 But instead of just claiming it, he says, if you look at this, this, this, this, this applies in the following fashion, he gives an argument for it. So he says, yeah, it seems to cover a lot of the material. So he always starts from the experiment up.

4:36 And then uses that to derive ideas that in some cases are very, very unexpected, but still come directly from what we see in laboratories. So, always focus on what does the lab actually say, what does it actually do?

4:51 And that's… that's a very nice feature of his work.

4:56 QED stands for quantum electrodynamics. This is an example of what is called a quantum field theory, although there's kind of an irony to that, because

5:08 As I talked about in some previous presentations, one of the major principles that Feynman followed was the idea of direct particle interactions for everything. So he has photons banging into electrons, for example.

5:21 He doesn't use fields. He uses particles. So, this is… this is a different approach from a large number

5:32 of theories that are called under… that fall under this category of quantum field theory. Quantum field theories usually assume space is filled with an omnipresent field of all sorts of…

5:43 magical vacuum pro… and I… maybe I shouldn't call it that, but to me, it seems a little magical. Magical vacuum properties that somehow know everything about what matter is and what it is. So in some ways, you don't… you don't really wind up explaining what matter is, you just assume that it's there in the form of this quantum field theory.

6:02 Feynman takes a very different approach in this. So, his quantum electrodynamics is a field theory, but he doesn't really invoke fields. He only invokes particles.

6:11 So, a quite different approach, and very different from that of Schwinger, with whom he co-won the Nobel Prize. And, Tamaganga is also more in the field theory category.

6:24 He would be a good person to do a presentation on. He did some great work on that, and he does not get as much attention as he should, as is often the case with these things.

6:35 Qed is also the title of a book. You can see a picture of the cover there. That's the old original cover, which I strongly prefer, because it captured, and I think this is the cover that was approved by Feynman himself, and the introduction that was approved by Feynman. There are later versions that have,

6:53 Not the intros that Feynman approved at the time. So, you can find a copy of the full book on the archive.

7:01 And, again, it's a nice resource, and well worth taking a look at.

7:07 So… when I say there are simple concepts, almost the first thing that Feynman starts out with

7:15 Was this idea that photons act like little stopwatches.

7:20 And, in other words, they just rotate at a certain speed, they can rotate at different speeds.

7:25 And with these stopwatches, they… as these stopwatches rotate, they move through space.

7:30 So, it's really as simple as that. It's an incredibly simple idea of you have this

7:36 Stopwatch, which is actually called a phase in quantum mechanics.

7:39 And then you have an ampli- you have an arrow, also called an amplitude, that just is the pointer for this stopwatch.

7:47 And it just runs through space, doing its little rotation thing.

7:51 And… If you think what a simple starting point that is, you go like, well, how does that produce

7:58 quantum field theory, and photons, and two-slit experiments, and all these strange quantum behaviors, and entanglement, and all… where does that come from? And that's kind of what's marvelous about the book, is he starts with these simple ideas.

8:12 And they're not analogies, they're actually re-presentations of the words that are used in physics. So instead of saying an amplitude, he does use the word amplitude, but at first he just says arrows, you know, just like an arrow. Instead of talking about phase, he just talks about a stopwatch.

8:29 And the reason is, there's no difference in the concept.

8:32 The fact that you have it incorporated into matrix algebra, and you have a lot of complexity in how you calculate it.

8:39 doesn't change the fact that the concept is quite straightforward. So, first idea is a photon has an arrow that rotates as it travels at the speed of light.

8:49 Which can vary in different media.

8:52 Second idea is that bluer the light is, the faster it rotates.

8:56 Now, you can guess pretty quickly, just from that, that this rotation speed is actually the frequency of the light. So, 1-1-1 matchup on that. You do one circle of this, that's one cycle of the frequency of the light. So, blue light is about twice as fast as the red light.

9:15 Now, here's a… this is actually an addition. I'll have this on my website, later today, but this slide… this slide is not in, and also every slide after will be off by one if you have a copy that you're using. So, just a… apologies for that, just small warning, but I thought this was worth adding in.

9:32 If you take that idea that you have a dial, and it's rotating, and it's moving through space along some path, what you wind up with is a spring. It just looks very much like a flexible spring.

9:43 This one is coiling in the left-hand direction, and I did that just because we started out with clock dials, and I didn't want to change the clock dials.

9:52 The mathematical representation usually is a right hand, so they would have the dial spinning in the opposite direction, but I just wanted to follow through with the analogy that was being used. And it doesn't matter, it's an arbitrary choice either way. So, you just have a coiling spring, go through space, has a direction to it.

10:08 And the way Feynman uses this, this is important, he uses it as a single unit.

10:14 And, that is where he had his biggest insight, is that you could take this timed representation.

10:22 The way the photon goes through all of time, through a long stretch of time.

10:26 And that you could use that as the full representation of the photon. Most people did not do that. Dirac was the one who came up with this idea, and Feynman just loved the paper that Dirac

10:37 Had done proposing this idea.

10:39 But, it wasn't the one that you people usually use. They like the idea there's a front of time, and that each one of these steps that you see here are just the ones that, that go through as you, as you move through time. So Feynman found considerable value

10:55 By taking this variational approach of looking at the entire path.

11:00 Now, I do want to point out a couple things. These are… these are assumptions that are hidden

11:04 in this model, and it's worth pointing out, the first one is that the S&D point, the source and the destination.

11:12 They're assumed to be in a single inertial frame. There's a mapping to a single inertial frame. You can have cases where one might be moving. The point is, it's a probability… you have an emission, then you have a probability of detection, all relative to a well-defined single inertial frame.

11:30 In many physics presentations, I always like to point this out, because it is so often ignored when people are using a single inertial frame for their coordinate system.

11:41 And you're talking about relativity, so you want to specify that.

11:45 Because as soon as you tie down that fashion, you've also put other limits on what it is that you're talking about that you have to be careful about. And you're saying that there is a set of previously defined information that correlates S and D.

11:59 You literally have to have clock systems that exist in both points, or it becomes unmeasurable, which is a point Einstein made back in 2011. Without any clocks, you can say what you want to abstractly, but you don't have a way to measure it, so you have to have a coordination operation.

12:14 That goes on. So it starts getting complicated. It starts looking almost like a… more like a program than it does just, like, a simple existence, you know, here it is, time is this. No, you have to… you have to have some steps to make that time measurable, as Einstein talked about.

12:30 Back in 2011.

12:32 So, another thing about these, this is… I think this one's fascinating, and it's kind of subtle, is he has these, these…

12:41 Lagrangian length… variational… Springs.

12:48 And he shows how they can bend out in different directions. Well, one little caution in that. Every time you bend one of these things, the speed of light still applies.

12:56 And it turns out that quantum theory does have some tolerance for the speed of light to have some flex to it. I mean, Feynman talks about that explicitly.

13:05 But the variation is very small, especially at large scales. So when you draw one of these springs and you bend it way out some weird, convoluted direction.

13:15 You can get a case in which the time involved with that is just completely outside of that inertial frame between S and D.

13:22 So, there are some inherent limits on this model that… and this is… I haven’t seen this discussed in Feynman’s literature, so I don’t know if he ever addressed… directly addressed it.

13:32 He certainly thought about it, because he thought about everything.

13:36 And I think the way he thought about it was just in terms of the probabilities of how weak they get. The probabilities get so small.

13:43 for a big loop, that you can just ignore them, but they’re still there. This is also, by the way, this flexibility, the fact these things can move and bend and buckle in different ways in time. It’s where you have some of the quantum uncertainty about time, about when does something arrive? So, interesting little things go into this simple model with that.

14:03 But it’s worth keeping in mind. So, one inertial frame.

14:06 Speed of light still applies over that path. A very long path is going to require a long time for the photon to travel over that path.

14:14 for it to become a real path. So you can have the virtual path, but not… not the static, you know, you can’t… you can’t really send a photon

14:22 Unless you take that full length of time.

14:25 So, one of the other things that is… It’s subtle, and…

14:32 And again, this is one I wish was talked about more. If you take the full elaboration of all these different potential particle paths, because Feynman talks in terms of an infinite number.

14:44 of these virtual particles, of these particle… these integrals of all paths. And…

14:51 you map it into something where you start paying more attention to time, so there should, for instance, D on the right here is moving in time.

15:00 Then the model you come up with looks

15:03 It doesn’t just look like, it is a wave model. It turns into a wave model.

15:07 So one of the reasons why a photon, for instance, if you… the wave model of the photon is you have one photon is irradiated out.

15:13 It goes in a hemisphere, it goes out like this.

15:16 And if you look at that in terms of the Feynman model, that’s the same thing. He’s saying you have all these paths… path integrals exist.

15:24 But he’s really just saying that there’s this… there’s this wave expanding. The two statements are equivalent with that, so you don’t usually get that equivalence, but I think it’s worth noting that, that there is an equivalence to wave models with this. So photons look like extremely diffused waves going over incredible distances, or…

15:43 They look like a large number of these.

15:46 Paths over time, also covering that same distance.

15:53 Another part from the review, there’s a thing associated… you got a rotating dial.

15:59 You’ve got a dial phase, and the length of that arrow can vary anywhere from 1 down to 0. 1 means that you have 100% chance of finding the photon.

16:09 And 0 means you have 0% chance of finding the photon.

16:14 Everything in between is the smaller circle that the dial sweeps out.

16:20 Now, if some of you have… if some of you know the physics of this, you say, no, wait a minute, isn’t it supposed to be the square? Isn’t it supposed to be the complex conduit? Yes, it is, it’s the same thing. What happens here is when you sweep out that area, you're squaring the length of the arrow.

16:35 So, these turn out to be exactly the same statement. This is just a more visually

16:41 visceral way of seeing what that means to square it. The squaring it is saying that you're taking a subsection of this cross-section. This works great, by the way, with wave functions. You have a wave function where you have a

16:54 It goes like this. If you spin it around like this.

16:57 then the probability just becomes the area enclosed inside of that wave. So this is actually a very handy way to understand what they mean by a probability density, or probability of finding a photon. So, in terms of probability theory, quantum theory is always probabilistic.

17:15 If your hand length is 1, you're gonna find the photon. It's gonna be there.

17:19 If you're handling a zero, you're not going to find anything. The photon will never be there. It's actually, in some ways, being restricted or prevented.

17:27 from going into that area, and you can very definitely prevent photons from going into error areas, that's how you… that's how you create mirrors.

17:35 So, in between, it's not linear, though. So, if you say, like, it's half the length.

17:40 No, you don't get half the probability, you get .25,

17:45 you get .25 with the probability, because you have to go by this little area. So you want to be careful that you don't just overly generalize in your head going from 1 down to 0, because in between, it's a little different. Not terribly different, but you have to go by this area concept.

18:01 when you… Two ways of interpreting that probability.

18:08 If you have an enormous number of photons, it's just how many photons you're gonna see.

18:12 And that's… it just becomes ordinary light intensity. So if you're shiny a laser, you have some probability like this, you will find out that, in this case, on the left-hand side, you have a… all of the photons are going to make it, the laser is going to send everything to a single spot, or almost everything.

18:29 And if you have something in between, increasingly less numbers of photons. So, at the level of perception of most devices in our world, that looks like a smooth curve, but it never is. There's no such thing as smoothness in the classical world. We think there is, but that's only because we have huge numbers

18:47 of photons and electrons and particles. So what happens is when you get sparser and sparser, and you go down to, like, one photon, which is the smallest unit that you can actually give.

18:59 At a given frequency.

19:00 Then the same idea transforms into a probability of that photon hitting.

19:05 And if you think about it, that comes out the same way, because each photon has a 50% probability, or a 25% probability, then a whole bunch of them, the whole thing is going to have a 25% brightness of what it would have had.

19:19 So they're really the same statement, but it's an important idea for understanding how this probability works in terms of intensity. There's a very close relationship between the intensity of light and the probability of light. It's so close that, in many ways, they're just… they're versions of the same statement. We just don't see that

19:38 Because we're used to thinking of light waves as a continuous, smooth phenomenon. But it really isn't. It always breaks down into these occasional flashes of light, and when you get the flashlight.

19:49 That's the essence of quantum theory, is that you get a full flashlight, the full energy

19:54 of the light hits.

19:59 Another part of the review, these arrows can add up with each other.

20:04 And the adding is just nothing more than daisy-chaining arrows together. So you take one arrow this way, you have another operation that you do on that arrow. These are transformations, it's like you're driving your car and someone tells you to turn right. Well, the blue arrow there is you turning right.

20:20 So, first you go left on the green arrow… green, that's your first operation. Then you go right for a right…

20:27 Right-ish from that, area from there to the… in the second one.

20:32 And when you add those together, lo and behold, you find that your destination is another arrow that goes in between.

20:39 those two points, except it goes directly. So this is not that different from driving. You're just saying, like, you know, cascade these arrows together. Whatever you get as the final result is, to use the old expression, is as the crow flies, which I've always wondered if that expression is an American expression, a European expression.

20:56 It might be a global expression, I don't know. Maybe crows fly in a straight line everywhere, but as the crow flies, as they say, at least in parts of the United States.

21:06 is your final result. So that's all this addition is. You have these…

21:10 different lengths, you have turns, and then you may go a shorter distance, a longer distance, it varies, and then you wind up with a result. So…

21:19 While this is a very straightforward concept.

21:23 getting a good mathematical representation, especially for large numbers of items, can get complicated. But again, the idea is to keep in hand is that I understand this, I understand driving, I understand…

21:34 Going green so many miles, going blue so many miles, and then having a net result as crow flies at the end of that.

21:42 Very important concept for understanding.

21:44 How photons and other quantum particles work.

21:49 Reflection.

21:51 First thing I'm gonna jump into…

21:53 It's about this curious thing about reflection.

21:57 Now, we all know how reflection works, right? If I take a mirror, and I put it on a flat surface, and I shine a light, you know, if the sun's out there, I can see the sun, it shines straight in, goes at an angle of incidence is exactly equal to the angle of reflection.

22:14 And I can put barriers in front of it, and I still see the sun there, so I say, oh, okay, so the photons obviously go from S

22:22 to the P, which is the destination, you say P for photo multiplier.

22:27 So, so you get S, and you go there, it bounces off and goes in a certain direction. So, seems straightforward.

22:34 Now, the interesting thing is… That is not how quantum theory works. It's… it's not even close.

22:45 the idea that Feynman quickly dumps on you is saying, like, no, no, actually, the photon can go anywhere. It can go anywhere in that mirror, almost with the same probability. So it can go over to A, it can go to B, it can go to D,

23:01 G is the one that corresponds pretty closely to the classical definition of reflection.

23:07 That's where our minds just scream, that's gotta be where the photons are going, because, you know, photons are particles, they come down here, they go up there, boink, they bounce like a little rubber ball.

23:18 That is just… our brains just scream at us, that has to be the way this works. Except that it isn't. And when I say it isn't, I mean by… not only just by mathematics, just go look at a CD and look at the colorful

23:30 play of colors. Look in the back of your credit card at the little hologram there. None of those things work that way. None of those have the photons going to one spot.

23:39 All of them have each photon going to the whole thing.

23:43 So this is not just some abstract concept. This is… this is the way things work.

23:49 On some very practical examples, once you get away from the simple example of a nice, flat, perfect mirror, which can fool you.

23:57 Because it makes you think things that are not really quite true.

24:00 So, this is his assertion, and the whole point Feynman's trying to make is, say, that doesn't sound right, that can't be right, so he wants to get into that and say, well, let's look at it, let's see what happens when we try to do that. So the first thing he does, he divides it up into a whole bunch of little bitty mirrors. You know, he breaks it up.

24:18 Into tiny little mirror strips.

24:22 So this is a case where breaking the mirror is not a bad idea. This is a good thing to break this mirror. So you break it up so you analyze, and of course, this is just classic mathematical analysis. Take your big problem, break it up into small pieces.

24:35 Where for each piece, you have a very uniform situation. That's the idea here. It's the essence of calculus, is break things up into smaller enough pieces.

24:44 And those pieces will tend to be smooth. By the way, that is not necessarily a characteristic every universe would have to have.

24:51 We live in a universe where that's true.

24:53 And it's a darn good thing that we do, because if it didn't, a lot of what we depend on to exist wouldn't work that way. But we have a universe where things generally tend to get smoother when you get smaller.

25:05 And this is something that Newton first contemplated, realized he could get away with it, but it’s not a given. It’s easy to come up with mathematical structures where that’s not true. Any kind of a fractal structure, that’s not true.

25:18 So, for mirrors, it is true.

25:21 And Feynman dides it up, and you have all these little mirrors, and I say, well, let’s see what happens at each one of these mirrors.

25:27 Alright? So, first thing you notice is.

25:30 Is that you have different lengths of the past, and that turns out to be incredibly important for understanding what’s going on.

25:36 you’d think it wouldn’t be that big of a deal. You know, it doesn’t seem like, well, like, so what? The paths aren’t that different.

25:42 In length, I mean, it’s a little bit longer, but not enormously longer.

25:46 But he says that if the source photon goes to A and winds up in the photodetector P, it has one path that it shows as a longer way. If it goes from S to point G, you have a shorter path.

25:59 Where it goes from, you know, add those two lines together, and it’s shorter, not an enormous difference, but it will be different.

26:09 And, of course, the directions you’re taking are completely different in these cases.

26:14 So, now here we start getting messier diagrams, but… but just keep in mind, this is not…

26:20 The ideas here are not complicated, it’s just piling a bunch of them together, so you have to show that… what happens if you put all of these together.

26:29 Keep in mind that… that… that spring thing I was talking about earlier, the idea that each one of these photons is like a little spring, so each one of these straight lines is actually representing a little swirly line, goes down to A, and then just keeps on swirling, goes up to P. So you have two… two branches, you’ve got two curly, springs.

26:48 At a certain frequency.

26:49 So each one of these has a different pair of springs. You have a… you have a spring, and I don’t know if my…

26:56 I’m assuming my mouse is visible to you, since I’m sharing full screen. So you have this one, and this one or two springs that count together, and each one of them has a number of spring cycles in it, so it has a certain number of cycles.

27:10 Same thing for this one, and this one. So you can see there’s a whole pairing that’s going on with this. Now.

27:16 Drop down from that, and say.

27:18 well, what is the full time? What is the full distance that I’m going to wind up doing with these different, different lengths? And what happens is your distance is longer for A, because it’s going way over here, you’re backtracking. So it’s going way over here, it’s going way over here, so you have this longest length here.

27:37 And then for… as you go in here, the links get shorter. Now, as you get right around here.

27:43 F, G, and H.

27:45 they start kind of flattening out, and they all have about the same length, so the X's are all about the same level.

27:52 And then it starts rising again. So over here, you see these longer lengths again.

27:57 Now.

27:59 This figure here, all this figure here does is… remember what I said earlier, that all of these correspond

28:05 to a rotation. So, if you have a longer path.

28:09 you have a certain amount of rotation. If you have a somewhat shorter path, a different rotation. So each one of these is going to have a different resulting rotation of that little vector, that little arrow that's attached to the photon.

28:23 So, look what happens. If the lengths are almost the same.

28:29 It's not too surprising to think that, yeah, they're going to have approximately the same length here, they're going to be approximately the same rotation, so they're going to be pointing in roughly the same direction, because they haven't changed much in direction.

28:43 They're all going about the same distance. So I have this bunch of arrows, E, F, G, H, I, which are these ones right in the middle. You see where it kind of flattens out here?

28:53 And those are the ones where all the arrows kind of point the same way. It doesn't matter which direction they point. They could be pointing up, they could be pointing down, sideways, that's not the issue. The issue is, do they point the same way?

29:05 And the way you can find that out is do this addition process I talked about, just again, just follow the directions. You have these little arrows. Now, the directions you're taking

29:14 are these… these final results of each of the photons after it's traveled at, so you're setting up a little… it's not the same travel path that you're doing here. This is one just using these lengths, the end lengths of the photons.

29:27 So you start at A, goes this way, B, C, and each one of these changes pretty dramatically, because you've got to see a huge change in length there. So they just go in totally different directions, so they just kind of spiral around here for a while.

29:39 And if you did this in detail, just there literally would be a spiral here that just kind of slowly opens up.

29:45 And then they start evening out a little bit, because you're seeing down, oh, okay, they're really… the links are winding up with the photons pointing in about the same direction. So these photons…

29:57 In the middle, Wind up forming a long arc here.

30:02 And then you get back into this chaotic little spiral again. They start going…

30:07 Why? Because the links are changing dramatically with each one of these reflections.

30:13 They're no longer… each one's adding a lot of length, so you wind up over here, and each one makes a huge difference in how it goes. So, the links, the ways the photons are pointing.

30:25 Keep going around little circles.

30:28 Well…

30:29 Remember, the rule is, as the crow flies, you’ve done all these little navigations here, following each of the photon results. You had a long stretch in the middle, and you went into chaos again.

30:40 But you still have a net result, and the net result is this one.

30:45 So, what you’re seeing is a result that’s being dominated by these ones in the middle.

30:51 And it does give you a strong overall amplitude.

30:55 for how this… for how this works. So it’s saying that there’s a good chance

30:59 That the light, that square, that…

31:03 Enveloped circle of this will be out somewhere out here.

31:08 So let’s look at the next one.

31:11 Actually, the same, same thing, just showing this, emphasizing the same point again. You’ve got this sequence here, arrows here.

31:19 Net sum here.

31:21 And the point that is… Worth pointing out here, Is that the amount…

31:31 That works, the past that worked the best, that had the most.

31:35 If you look at it, those are the ones that take the least amount of time.

31:39 Because that’s where these arrows start to point the same way. They sort of, you know, focus in right here.

31:44 So, somewhat magically, you get this little result here, where whatever’s the shortest path.

31:50 is also the path that winds up getting amplified. You start having these little additions to these arrows.

31:56 And they all add up to the same thing.

31:59 So, this is a calculation, and the photon is doing it for you.

32:05 Because it’s adding all these different little paths.

32:08 And you don’t have to worry about it. Photon’s taking care of it. And look how many paths it… it’s just… this is an approximation. The photons take one photon!

32:16 Not a bunch of photons, one photon.

32:19 It’s taking care of all of these different calculations for you.

32:23 Figuring out that here’s the ones where they all kind of converge and start going the same direction. It adds those all up for you, and it gives you an arrow that says.

32:35 I really want to go this way. I want to go about to where G is.

32:40 Which, lo and behold, is the classical incidence angle.

32:45 So, what happened here? It’s… the assertion that Feynman’s making in this is that because light sees the entire mirror, because it is not a ball, because it does not just bounce off the middle.

32:58 But because it sees that entire mirror.

33:02 That makes it possible for it to figure out, hmm, what’s the best path?

33:06 And it figures it out for you.

33:09 And, this is, again, a remarkable amount of calculation is going on.

33:15 By a single photon in order to come up with this result.

33:19 And the result is, even for that single photon, you’re going to get a very high probability every time that it’s going to go from here, from the source.

33:28 to the photomultiplier. So… If you compare that conventional computation.

33:35 Wow. If… if you try to… if you try to calculate this using GPU chips.

33:43 You are gonna get an enormous, enormous consumption of energy.

33:48 Just to come out with this same result of saying, here’s the shortest path.

33:52 And that single, silly photon’s doing it for you at the speed of light.

33:57 With almost no energy. So, talk about energy efficiency. You know, you should give the photons credit. They do some remarkable things.

34:07 And Feynman’s QED method helps emphasize what’s going on with that, the fact that this is… this is a remarkable result.

34:16 So, I already mentioned how these things spin in circles.

34:21 And that’s the next emphasis. What happens?

34:24 If the majority of the spends just keep going, blah, blah, blah, blah, blah, blah, blah, you know what you get? You get zero.

34:30 You get nada. You get nothing.

34:32 Because they go in a circle, and that circle is like spinning a loop, and at the end of the day, you can spin in this loop all you want to, and it still adds up to zero. So you just get nothing.

34:44 And that’s a remarkable little feature.

34:48 ease.

34:50 arrows.

34:52 So.

34:54 If you’re properly skeptical, and especially if you’re used to thinking of photons as just little balls that just boink, boink, bounce.

35:02 You want to be a little…

35:06 you should be a little skeptical. You say, well, you’re claiming that these things are bouncing off the whole mirror, that’s a little hard to swallow. How about if we, you know, can start waving check that? Say, yeah, there is.

35:19 Because when you have very small little arrow sections here, you get little pieces where, yeah, they’re still more or less in the same line, because it’s small enough that they haven’t changed, the distance hasn’t changed that much. And then you get to a thing where they’re out of phase.

35:33 Where they go in the opposite direction. So, you add these up with these, you get that circle, you get nothing. But what happens if you take these guys out?

35:42 You’re taking out half a circle.

35:44 And you take these guys out. You took off another half the circle. Well, what happens? Well, you start to do your spiral, so you go around here, you go whoop, go up to there, and say, oh, wait a minute, there’s nothing there anymore.

35:56 Oh, oh, here’s my new arrows, they’re coming from that other place, okay, and so I start adding up here.

36:01 That gives you a strong signal. So you’ve split your circle in half, you’ve erased half of two circles.

36:07 And you wind up with one pair of half circles.

36:11 And you get a strong signal. And then you have to say, is that real? Does that actually happen that way? Of course it's real! That's a diffraction grading! Anytime you see a beautiful play of colors.

36:22 Off of an object that has lots of lines.

36:25 You're seen in diffraction grading, you see this on CDs, you see it on the back of your Visa card, you see it on so many objects. Not the iridescent objects, though, that's a different kind. That's the effect I talked about in the last talk.

36:38 But when you see it from surfaces that have been ingrained with small lines, which are very common these days, when I was a kid, they weren't common at all.

36:46 That's a diffraction grading. And another point, the first point is.

36:52 it kind of proves that the photon's reflecting off the whole thing, because otherwise, you could not get that effect. You can't get that information

37:01 Without having all of those different segments of the mirror contributing a little bit to the final result.

37:07 And another way you can tell that something interesting is going on is if you send different colors of light, well, they have slightly different cycle times. So when you work that out, they still reflect, but guess what? They reflect at different angles. So you get the blue light tends to be reflected more.

37:23 Red light is reflected less, and the fact that diffraction gradients give you rainbow colors

37:29 is yet another proof that the photons, the individual photons, are seeing the entire diffraction gradient. It can be a very large diffraction grading, by the way. You could have a

37:39 You have a football field-sized fraction grading, and you can run an experiment from a plane showing that you have individual photons.

37:47 Individual photons. I don't know if anyone's ever done this, but it would be a fascinating,

37:53 Kind of proof of concept, if they did.

37:55 But if you had a football field side diffraction grading in the dark.

38:00 And you had a plane of high sending individual photons, better be a very dark night, but you have individual photons that you can recognize by their frequency or something, and you have another satellite out here.

38:11 You can actually show

38:14 an enormous probability increase when those photons hit the entire field, and they go off in this direction. If you make a brighter light, you'll see the entire field shine in that color of that light.

38:25 So, again, this is… this is a scale-free phenomenon.

38:31 You can increase it to any… to the best of our knowledge from any physics we've seen, you can increase it to any size you want.

38:37 It still works. The photon still goes everywhere.

38:41 We don't see it so much in diffraction gradings. If you look at,

38:46 If you look at the refraction effect from Einstein lenses.

38:51 You can see photons going through 10 million light years of refraction.

38:56 So, there's no… there's no scale limit to this, as far as anybody can tell. It's just the way the universe works, and that in itself is remarkable, because

39:05 You think, how can all these calculations be going on at those scales?

39:10 And still work. And yet, we see that. Every time you look at an Einstein lens.

39:16 You're seeing an enormous number of these paths by refraction, not by diffraction.

39:21 going on.

39:24 This goes in the other direction, too, because, think about it, crystals, salt crystals, she's an ordinary crystal of salt.

39:32 pretty much an ordinary crystal of anything. If you send in X-rays, which have wavelengths that are about the same size as atoms, wow! All of a sudden, everything starts diffracting like crazy.

39:46 Because you're doing the same thing. You're doing the same thing you showed out. You're creating little mirrors that are reflecting some of the X-rays and some of them out, and if they're at just the right angle, you get this powerful signal. It's the same concept, it's just at a smaller scale.

40:01 This is incredibly useful for all sorts of chemistry issues, trying to understand the structure of matter. This is how DNA was first uncovered.

40:14 was using X-ray diffraction. Watson Crick had nothing to do with it. They just, they just stole the data, frankly.

40:21 But the X-ray diffraction work,

40:24 is what made it possible to determine the structure of DNA. So, a really powerful effect occurs at every scale.

40:37 Now, that shortness of path… this is just worth going over again.

40:42 Time is least. When you get to that path.

40:47 A way of understanding how remarkable that is, is try to think of this. You are a lifeguard.

40:54 you see, some big burly guy who thinks he's a good swimmer, and he's not out there, and he's drowning, so I say, what's the quickest way that I can run there, and get out to him, and get there in time to save his silly hide, because he didn't realize what a bad swimmer he was.

41:09 And the intuition is, if you're not a lifeguard, is that you go straight out

41:15 to where the water is shortest, and then you go down. So you would go down. All the way to here, you go to here, you say, okay, surely that's the fastest path, then you drop down so you have the least amount of water to swim in. Guess what? That's wrong. That is not correct.

41:29 Our intuitions, as our smart, big brains think we've got it all figured out, we don't do very well in this. We tend to think of it the wrong way. The actual answer is something in between, and the way you find it is the same way the photon finds it.

41:46 What is the time it takes to do this? What is the time it takes to do that? And then you figure out where you're going to get the best path as a sum of these. We don't think of it because we don't think in terms of wave cycles. Photons think in terms of wave cycles. We don't.

42:02 We just think in terms of distances, so we kind of oversimplify the problem a bit too much.

42:07 So the actual distance

42:10 is neither going straight… certainly not this way, you know? You're gonna be a bad life… you're gonna be a bad lifeguard if you go out to A and come out this way, so don’t do that. Nobody’s going to approve of that solution.

42:23 It could be excused, at least for the first time, after you maybe lose a couple people, if you go this way, but hopefully you won’t do that either. So that is also not the fastest way. Another way it’s not fastest is to go straight to it, because then you have too much water.

42:39 And you wind up wasting time. So the optimum path Is this one here.

42:44 And good luck figuring out exactly what that is if you’re a lifeguard, because it’s a complicated

42:50 A little complicated bit of math.

42:53 But not for a photon!

42:56 A photon, a photon with so little energy, they can barely see it, can figure this out lickety-split, and say, okay, oh yeah, I want to… okay, here it is, right here, that’s where I want to go.

43:08 And, because of this integral of all possible histories, this enormous amount of implicit calculations that photon does, it figures out that path without any trouble, at the speed of light!

43:20 And, can get there faster than the lifeguard can. So, don’t underestimate the processing power that goes on in quantum mechanics. It’s really, truly remarkable.

43:32 Water reflects because… water looks like water because it’s reflecting the sky. Do you ever think about that? The main reason water looks blue

43:40 In most cases, there is actual blue water, especially if there’s a lot of carbonate in it, but in most cases, the reason water looks blue is because it’s reflecting the sky. So you have blue sky, you have the surface of the water, you see this blue color, and you interpret that as being… that’s water, because when you see sky in the ground, that’s considered water.

43:59 Unless you have an optical illusion, you have a mirage over a road, the warmer air creates a lensing effect.

44:07 The light comes down from the sky, looks at that, and says, okay, I gotta do all my calculations. Okay, you guys, all you virtual photons, you go this way, I’ll go that way. All right, let’s all get back together. Okay, here we are. Yeah, here’s where we want to go. We want to go this way.

44:23 So they all do that lickety-split speed of light, and they wind up reflecting the sky over that section of warm road. So you have this…

44:31 One of the great ironies of nature, that the spot that is the hottest in the place you don’t want to go

44:37 Looks just like a wore… a nice, cool pool of water.

44:41 And, Mirage, indeed, a dangerous one, one that has cost people their lives. But it all goes back to these photons figuring out what’s the shortest path?

44:53 Now, I mentioned this one earlier, and this is one where I want to put a little careful

44:58 Note about that is photon point, Feynman…

45:03 Feynman delights in pointing out the absurdity of quantum mechanics.

45:09 And now that absurdity then turns itself into exactly what we see.

45:14 And one of the ways he points out his absurdity is saying, there’s no reason why light can’t go out here.

45:20 and wiggle around, you could do loop-de-loops, for that matter, and then come back to P.

45:25 Or it could go this way, and do more loop-de-loops, and come back to this way.

45:29 But his point is that for those loops also.

45:34 They're not the ones that give this optimum, shortest, least time path.

45:39 They just don't. They just… they just wind up going into chaos. They go into little circles, going around circles again. So all this just disappears into a bunch of little circles, going nowhere.

45:49 And the only paths that come out are the ones that look like a straight line.

45:53 So, this is a useful approximation. This is where Feynman emphasizes the importance of using the approximations that summarize a result you already have so that you can simplify the overall problem. So, you can take all this and say, you know, I really don't need to worry about this part, although

46:11 If there are unusual circumstances, I do.

46:14 And that's the qualifier. So you always say that if there's some weird case.

46:18 where there might be some refractive components out here that could bend this around like this, then I have to pay attention to that.

46:24 But for just a homogeneous environment where everything's smooth, I don't have to pay for some… I don't have to pay attention to something like that. I can just approximate the path of light as a straight line between the two reception points. So that's a very handy thing to be able to do.

46:41 The little qualifier that I gave earlier.

46:44 Is that, again, the source and the photodetector are in the same inertial frame.

46:49 The time it takes at the speed of light to go from here to here is determined by that inertial frame.

46:55 Barring very unusual circumstances, all of this stuff here is way outside the time limit provided by the speed of light. So if light tried to travel one of these paths, if you actually gave a little burst of light from here.

47:09 the burst of light would only get about this far by the time the other light had actually hit. So there's a hidden time component in this, and Feynman's QED analysis is very atembral. It doesn't look at time, it looks only at the Lagrangian, at the time dimension.

47:24 But it's worth keeping in mind that there is a time component to it also. It takes time for these things to form, and if this path goes too far out there, it's simply not relevant, because there's… by the time everything is completed, by the time

47:38 With 100% certainty, the photon has arrived here, in some cases, if you have a focusing lens.

47:43 There's no chance that they… the pass out there are gonna have any effect on it. They don't have time to come back.

47:48 And have an influence. So there's some odd limits there. I keep meaning to look to see if there's some articles. I would love to dig into the literature and see if there's been some discussion of this, but generally the QED framework doesn't… isn't looking for that, so it doesn't really get into those issues that much. But there are some speed of light issues.

48:09 Why lasers go straight? If, if I take out my, my, my little, I have one of these little…

48:17 combination lights that I carry around. It has a green laser, it has an ultraviolet light, and has regular light. I love it.

48:25 But it just amazes me to watch the difference between just putting regular light setting, I get a diffuse white light, and then that green laser setting, where the lights, photons just seem to go straight in arrow. Well, isn't that a proof? Doesn't that show that photons are little balls that just fly through space?

48:42 No, it is not. It emphatically is not, and this is just one of those things where the intuition can be,

48:53 Very… Very deceptive.

48:56 If you have that laser, green laser, going through this little slut, and green laser might be only, you know, a few millimeters wide.

49:03 It will go straight as an arrow for an incredibly long time.

49:07 But if you think it will go for an incredibly straight… straight like that for an indefinite time, it doesn't.

49:13 What happens is, eventually, that wave starts to spread out. How much does it spread out? It depends on how wide the slit is.

49:22 If the laser, and they do this in an actual laser beams, they'll take a laser beam.

49:27 shoot it backwards through a telescope to go out this way, and then the laser will stay coherent, will stay into a tight beam much, much farther than if you just shine the light that way. So this is a trick that they actually use to make these laser beams stay tight

49:42 For a longer distance. But ultimately, the lasers have to go by these path integrals. And if you don't have enough path integrals.

49:51 then you will not wind up with this 100% chance of getting the laser photons here. Now, if you use wave theory instead, so I mentioned there's an equivalence between QED and wave theory. This is one where the wave theory actually comes out a little more intuitive.

50:07 If you look at a photon or light in terms of wave theory, when you put a wave through a very small aperture, it turns into a hemispherical wave front going out this way.

50:17 And then you say, well, then everybody's got a very low chance of seeing the photon in that case, and that's exactly correct. So, the QED analysis is a different way of looking at the same thing, but you get the same results.

50:29 The wave analysis says I have this probability wave, which is always fun to try to figure out what is a probability wave.

50:36 But it is a wave, and it also has actual momentum to it. It can actually… it can push things.

50:43 So, if somebody tells you that a photon wave is just an imaginary construct, no, it's not. It pushes things. So the photon wave will go out this way, and

50:57 And Will?

50:58 move things aside a little bit. So the wave model comes in quite handy in cases like this. The QED model just gives you a way of keeping the particle perspective, but still coming out to the same conclusion.

51:09 And the conclusion is that if you make that aperture too small, you wind up with photons going all over the place. Why? Because you do the additions, you've got those little line segments again. We're using that line segment approximation that Feynman derived.

51:22 So you count up the number of cycles in these, and you say, how does it work out? And it turns out that there's not much difference anymore. You get a… they point different directions, you get a point, a net pointer this way here, a net pointer that way there, but the lengths are still comparable.

51:39 So you say, yeah, a photon could go here, it could go there, I just don't know. If you send a whole bunch of individual photons instead of a laser pointer.

51:50 you'll wind up with random hits on both of these. Incidentally, when you see discussions about the two-slit experiment, where they have two slits, and you say, like, if I shut off one slit.

52:00 You know, the photons go straight out the other way. That's not true. It's just… that is… that is so not true. You can't get the two-slit experiment until the slits are so small that they do this.

52:14 Until they are small enough for the photon to have a chance of going here, or here, which would be the shadow of the other sled, until the apertures are narrow enough to cause the wave to spread in all directions, which is a very quantum phenomenon.

52:30 then you can't get a double slit. So, saying that you shut off one slit, and then the photons then go straight through the other one. Anytime you see a video, you see a YouTube, you see someone discussing it, you see the assumption yourself that that's true. It's not true! Don't buy that.

52:47 Because small aperture means wide dispersion, period.

52:52 2-slit is based on multiple Y dispersions.

52:57 And if your holes are big enough that none of that dispersion happens, you'll just get two dots. You'll just get two laser beams going there, or you get one laser beam, however you set it up.

53:06 So, you want to be a little careful with that.

53:09 Focusing lenses.

53:11 I remember when I was very young, I was fascinated by lenses, and I thought they… they had to be made out of some incredibly exotic material that had this wonderful

53:22 property of magnification, and I think in some ways I was disappointed when I found out it was nothing more than the shape of the material.

53:29 I mean, the material did play a role, but I said… so I call it, like, the shape?

53:33 You mean it's not some magical property of the material itself? Well, you know, it has its index of refraction, but yeah, it's the shape.

53:42 And the shape is that if you just have lines, and you just have little scattering points, like here.

53:50 This could be a little bit like a diffraction grading. Got this one-line approximation. Again, we’re not bothering with all the different, you know, cases you could wander off out here.

53:59 So, single-line approximations, both cases, and you look at the odds on what this photon is going to do at this photoreceptor, and the answer is…

54:12 Oh.

54:16 And I’m looking at this…

54:20 I may have a… okay, I thought this was not the lens example. Let me look at this.

54:31 Okay, I do not…

54:34 recall exactly why Feynman put in this arrow at this point. Yes, there is a small arrow, for…

54:44 I think he… oh, he’s just pointing out… he was just pointing out, yeah, if you have these different pathways, there’s no object in this. I’m sorry, I was misinterpreting that. I was interpreting this as small mirrors or something.

54:56 If you just have… look at these pathways and say, what are the odds on any of these other ones landing light at this point? The answer is essentially zero. The light just goes sailing off in these different directions. It’s not going to suddenly bend back

55:08 And go to this direction. Remember, that is one of the possibilities that you have, that light can just go here and just say, oh, I’m going to do a right angle turn, kind of go right down to here.

55:19 So, if you look at the integrals in that, it just says, no, it doesn’t do that. The only ones that add together constructively are the ones right in the middle here, the ones right through here around M,

55:29 Those give you the strong amplitude here, and you wind up getting a signal that says, okay, only the light coming, that comes straight from here to here is the light that’s likely to arrive. So, say, okay, that makes sense, that’s what you would expect.

55:46 But, if you put a lens in the way.

55:49 And you say, you know, I’m still going with this idea that photons can go anywhere, and what if there’s something else out there

55:56 That, messes up that whole… that whole phase thing again.

56:01 Well, there is, and that device is called a lens.

56:05 What the lens does is it changes the phases of these different angles.

56:11 For the potential photon path that could go this way, and suddenly that photon path matches!

56:17 And says, oh, that’s a sing.

56:20 And then you shape the lens just the right way.

56:23 Where you wind up getting less change in the pathway here. The irony is that it’s less change on the edges.

56:30 And more changes in the middle.

56:33 And very counterintuitively, what you wind up with is that all of these paths that you thought were impossible out here

56:41 Wind up focusing in

56:43 into the same result. And the result is you get a very strong focusing effect. You get a very strong amplitude.

56:51 For finding that photon. If you see one photon, if you see a flash of light with many photons, what you'll see is this entire lens will suddenly become a brilliant surface that's all the light is shining right at you. It all gets focused under that one point. If you use individual photons, it's more random.

57:09 But the same idea. But I like the irony of this, because, like I say, the irony is, our intuition says, these are the paths that count. So those are the ones you might think need change the least. No, it's the other way around.

57:21 You slow down the paths in the middle, you slow down the ones that are going fast.

57:27 And make them wait and say, you gotta wait a little bit. Hold on here, just slow it down, slow it down.

57:33 And we're gonna leave those weird ones out at the edges, give them a chance to, you know, do their thing. So these guys going out there and say, okay, I see a probability for this. And those are the ones that are changed the least, and they're the ones that become real.

57:47 And there's a lot of irony to that, because you're making these bizarre paths suddenly become the real paths that are just as strong as the ones there. So that's how a lens works. A focusing lens is a remarkable device.

58:02 And I think we underestimate it sometimes, the way it works with the quantum world, and it's very quantum, because one lens… you put a lens out here.

58:11 and you put single photons, that entire lens… people tell you that quantum mechanics only works at atomic scales.

58:18 And it only works at cold temperatures? That's nonsense. This lens, the lens in your eye that you're using right now, is room temperature.

58:27 The thing is, it's transparent. It doesn't interact much with photons, except slow them down. That's the key.

58:33 So if you have a media like that.

58:35 It becomes a quantum transformation engine that says, for that one photon, I'm going to convert all of your different probability calculations so they all converge to here.

58:46 And they wind up at that one spot.

58:48 So, simple concept, remarkable, and very, very quantum effect.

58:55 And again, this is another one of my themes, is I don't like it when people say that quantum is only atomic, or it's only very cold, or it's only this. It's extremely common in anything optical. Optical is just a…

59:10 Wealth of quantum phenomena.

59:12 So is electricity, too, by the way.

59:15 Calculate sequences of events.

59:18 And… I'm gonna go through this pretty quickly. I'm already over time.

59:24 So… and I didn't expect to be able to…

59:27 get in too much detail on this. When you have a series of events, and really, we've been doing this implicitly.

59:34 You have something like a glass reflection, you have some pathway here, another reflection.

59:39 what happens with these photons, it's like directions. You know, you're doing it… remember I gave that example earlier that you go so far this way, then you turn back this way, you go another way, and most of these operations are just like that.

59:52 You have a turn, you say, I want to change the direction of the arrow, like a reflection. We'll do a 180 switch on it sometimes, sometimes it does zero.

1:00:00 And then you have a diminution, you have a reduction, saying, like, only part of it counts. So you get that combination, and you do these sequences.

1:00:10 of, operations. So, a sequence of operations is just multiplying the arrows. We've had the adding the arrows, where you just sum them all together by putting them end-to-end. But for an individual arrow, you also have this sequence of the steps, essentially the driving directions. You say, like, I want to go this way, go that way, go a little less, go a little less, and you keep shrinking.

1:00:29 And you wind up with these succession of events. So, that's your second part.

1:00:34 of really understanding photons. You have addition of the different paths, but you also have this multiplication

1:00:40 Which corresponds to the conversion of the photon in certain ways that it goes through it.

1:00:46 You have complex mathematical tools to do this, matrix operations, but the concept, again, is very simple. Driving directions.

1:00:53 Turn, go this far.

1:00:56 Go a little less, and in general, you shrink each time, because, you know, you're using up your gas.

1:01:01 And the photon only has so much energy.

1:01:04 So here we're talking about multiplication of lines. This is really just saying, you know, multiplying lines. Scale lines, so, you know, the amplitude scale, very much like multiplication.

1:01:15 the arrows come up with… right, here's some notations for this, and again, I'm going to skip over it pretty quickly, but you can see what's going on here about the multiplications.

1:01:25 Interesting thing about operations with photons is the very act of being a photon is an operation. A photon moves, it travels.

1:01:33 So, as it travels, it rotates. So, the distance the photon covers is an operation in its own right. You know, everything's in motion.

1:01:42 In everyday present, life. You can't have a photon

1:01:45 Except in some very special cases, they're just sitting in one place. So they have these rotations going on with us.

1:01:53 Now…

1:01:54 One of the things that Feynman gets into next is he goes through the same calculation again the first time, he goes through these combinations and multiplications, that is just the turn and shrink instructions that happen whenever the photon encounters something.

1:02:08 So, the photon encounters something, it does a turn, it does a shrink, and you add these together, and you get a result that almost looks right, and we got that in the earlier presentation a couple months ago.

1:02:20 To the point, too.
1:02:22 Except, if you go through this carefully.
1:02:28 You wind up getting answers That are wrong, so…
1:02:33 So, everything's an approximation, and here Feynman goes on and won't go through the details in this, but it's interesting to look at and stop and think about it and say, something more is going on with this.
1:02:46 If you just take the turn and shrink operations all by themselves, you don't get the right result, because you don't get… you get 108% in some cases, so something's… something messed up, something messed up with it.
1:02:58 What you're messing up with is something I actually covered more in the last presentation, which is that the photon reflects backwards and interferes with itself.
1:03:07 And if you add that interference with itself, which is a remarkable thing all by itself, it also kind of messes with your concepts of time.
1:03:14 Because it goes backwards, you know, interferes with itself.
1:03:18 How does an object interfere with itself in the past? Think about that for a little bit. And yet, that's what is going on here. So, it goes back, interferes, it reduces, and pulls energy off from the other reflection.
1:03:30 So now you get a more accurate approximation.
1:03:34 So, what happens with this is that photons… the ultimate principle that always applies, and I would put this down as the driver instead of as a consequence.
1:03:47 is absolute conservation of energy. It says, whatever you do.
1:03:51 One way or the other, the phases only help you distribute the energy.
1:03:55 They do not create it.
1:03:57 They do not eliminate it. The phases and the turning arrows, the shrinking arrows, all these actions.
1:04:04 with the arrows and with the little dials, are ways of calculating how the energy is going to be allocated, and they will always find a way. If one of them gets more, the other one has something taken away, and the arrows will always accommodate that. It's really kind of a… it's kind of a cool and remarkable thing.
1:04:22 how much they cancel. And again, it goes by taking the idea that the arrows have to go any way they can, and when you add all the different ways the arrow could go.
1:04:31 You wind up saying, oh, it came out with exactly the same energy.
1:04:36 And here he talks about another one. It's actually more reflections. You can have additional ones that go on with that. You have to take these into account. When you look at a rainbow, most of us, all of us have seen rainbows.
1:04:48 Most of us have seen double rainbows. Some of us have seen triple rainbows. Why does all this happen?
1:04:53 Because you're seeing a literal reflection of the same idea with photons. Photons will do whatever they can do.
1:05:01 If there's an opportunity to do it, they will do it.
1:05:05 And if conditions are good, where you get an amount of energy that allows you to have a second rainbow, you'll get a second rainbow.
1:05:12 If the conditions are really good.

1:05:15 you can get a third rainbow. And actually, the series continues after that.

1:05:19 So, the guiding principle is the total conservation of the energy, and the exploration of everything that could happen is part of it. You don't just suddenly stop and say, oh, okay, everything's done.

1:05:32 It just drifts off to very… you know, I don't know if anyone's ever seen a fourth rainbow. I don't know if that's an actual phenomenon that exists.

1:05:41 But there's certainly nothing in principle that says that it couldn't.

1:05:45 And that you could have additional rainbows beyond that.

1:05:49 One of the things to point out, this is getting into some different turf, and it's really leading into the next one. Everything I've been talking about so far.

1:05:56 About adding Arrow, about adding the paths.

1:05:59 About converting the paths with multiplication, so each path, you multiply it to give these little operations.

1:06:06 and then you add old paths at the end to get a result. That's talking about a single photon. Now, if you have a case where you have… let's say you have two photons, and they're being emitted by two sources.

1:06:18 Then it starts getting a little more complicated, because you think X and Y each are emitting photons.

1:06:23 One way that the result can happen is you can have the photon from X goes to A, the photon from Y goes to B.

1:06:30 So, here's where you want to be careful, because that is not the same thing

1:06:36 as X going to B and Y going to A.

1:06:40 Those wind up with different positives… different magnitudes and different calculations.

1:06:45 So, you want to look at these as different cases. Now, in the case of photons.

1:06:50 You don't see such huge results. In the case of electrons, oh boy, you see enormous differences between these two cases. In fact, that's one of the essence of what matter is. It behaves differently in the case of these two

1:07:06 cases being switched. So in the case of photons, it makes less difference, but the calculation is still different, and they are distinct cases. So you have to go through all of these distinct cases, you add the cases together at the end, but you have to be careful how you do it in between.

1:07:21 This is a little bit more like dice rolling. You know, you have two dice, you multiply the events, because, like dice, you know, if one gives a half… has a half chance of finding some number you want.

1:07:32 The other one is a half chance, then the product of that is you multiply that, you have a one-fourth chance of both of them giving that product. The same kind of a principle applies with this. So, this gets a… again, it's an interesting thing, it's a somewhat subtle thing, but

1:07:47 When you have multiple photons involved, you have to look at all the different cases of where these things, different configurations, how they interact with each other.

1:07:57 Double slate experiment.

1:08:01 Got small holes. Do they have to be tiny holes? Yes, they have to be tiny holes. Why? Because if they aren't both tiny, you will not get interference effects at all. They'll just act like lasers, or the light will just go straight through and make shadows. We see that all the time with ordinary shadows.

1:08:17 You have to make the hole small enough that the diffraction effect, the reduction in pass, makes it possible for the photon out the other side to go all sorts of different directions. Then you start getting interference effects.

1:08:33 You can get these.

1:08:34 Effects up until the point

1:08:37 where you try to get clever, and you say, well, you know, I want to see if that photon goes through there. So I'm gonna put a little detector, I'm gonna be real sneaky, and I want to see which way that fo… because I know it's just one photon of energy.

1:08:52 So it's got to go through one way or the other, right? You know, it's the same issue with electrons, but it also applies to photons. So you put the detector here, you put a detector there, and you say, okay, I'm gonna nail it. It went through this way. The moment you do that, all the interference disappears.

1:09:08 Interference does not work that way. The only way the interference works is if you don't know

1:09:15 which way the photon went, at a quantum level. Quantum level, I mean, if it went through a small aperture, if the path… if the path histories are so limited that the photon doesn't know which way to go.

1:09:28 That's when you get that. But the moment you do a detection.

1:09:31 You've short-circuited this whole process. You've made the D… you've moved the D point, you've moved this final destination up to here, even if you say, well, the photon's still going through, it doesn't matter. Once you have knowledge about that photon, once you know it went that way.

1:09:46 Then the whole concept of multiple interference from multiple locations just disappears.

1:09:52 It does not work that way.

1:09:57 summarize that point, Feynman goes through this really interesting discussion, that…

1:10:02 You take those different cases, so if you have

1:10:06 The leftmost case, where you just have 100% of…

1:10:11 you don't know. You don't know where the photon went. You just have these two… you have a photon going through two slits, and you take different distances, and you find that you get this remarkably

1:10:23 precise curve in which, you know, a certain percentage of photons go through, whether they're up to 4% in this case, or they go down to zero. And…

1:10:32 The other case is if you know exactly which hole they went through, plunk, it just disappears completely. You don't see anything. You get this flat line in B.

1:10:41 But the other thing is that if you get a mix, if sometimes you're able to figure out that information, sometimes you can't figure out that information.

1:10:50 Then you'll get… some of them will interfere, and some of them won't.

1:10:54 So, the thing that you have to be careful about, and everything in quantum history.

1:11:00 is… quantum mechanics is, is there a history available anywhere in the universe? Feynman states this more bluntly in one point, where he says, it’s not just enough that you personally are ignorant of it. You have to have a situation in which nothing in the universe has any trace of history about how that event happened.

1:11:18 And if there’s no trace of information anywhere in the history of the universe, recorded locally, recorded anywhere.

1:11:25 About how it happened, it will interfere.

1:11:28 Which is a… I like the oral version of that in his lectures. It says, you know, it’s always… it always interferes if there’s no way to detect.

1:11:39 And, it’s a great principle, and an interesting one. If you see things where people are wondering, like, is gravity going to affect quantum mechanics?

1:11:51 If you happen to be one of those people who’s looking at that, it’s a very interesting issue. But let me just suggest one point, is ask that question, did I get an information signal?

1:12:02 And if you have gravity that leaves an information signal of some sort somewhere, then you will not have quantum effects. You will have classical effects in the light. And in that, it doesn’t really matter whether it’s gravity, whether it’s chromodynamics.

1:12:16 If you get an information signal, if you leave a residue.

1:12:21 Then you will get some kind of,

1:12:23 loss of interference. The other thing is, you do not have to…

1:12:29 be, again, super cold, you might be super small. A lens does not leave information about the path of the photon.

1:12:38 Which is remarkable. You go to this… you got a great big lens, you got photons going through it, and you think, well, surely they’re none quantum actually went through that lens. No. As long as the lens doesn’t interact with the photon beyond slowing it down, as long as the lens has no record, no record whatsoever, of where the photon went through the lens.

1:12:57 It behaves as a quantum device. It records no history, and you get a full lensing effect. The moment you make that lens start trying to say, oh, did the photon go here, here, here, here? You’ll just get a white surface. You won’t get a lens. The lens disappears.

1:13:12 It turns into an opaque white mess.

1:13:14 And you’re getting nothing So, quantum effects…

1:13:19 Very much count on whether information is created

1:13:22 at whatever temperature, at whatever scale. It’s one of the reasons why claims that brains could have quantum quantum interference make a lot more sense to me now than they used to. For decades, I didn’t believe that, but there are a number of effects that can go on that are related to laser effects inside of

1:13:40 Ordinary thermal systems.

1:13:42 that have characteristics of this quantum interference. So, it’s trickier than just saying, like, well, it’s got to be, you know, impossibly cold or

impossibly difficult. The question is whether, is it fully transparent? If it's fully transparent, then it's quantum.
1:13:58 Photons, it's clever explorers. Photons… In summary,
1:14:04 they are just so smart, it just… I just… I can't get around that.
1:14:10 How does one photon do all this?
1:14:13 It can go out and calculate
1:14:16 All of these different things, and if you have a case
1:14:19 Where it's focusing that photon back to a single, single point.
1:14:25 With a very high probability, you can see the results of all those calculations each time.
1:14:30 And it's the least time calculation. It's just getting its idea of least time, and the photon will explore everything for you.
1:14:38 You don't have to, you know, you just set it up, and you want to explore something, you put that in its path, you do some kind of lensing. There's got to be some potential, and I still think it's unexplored potential.
1:14:49 for, quantum calculation type of uses of this, that… how can we do this to make things work better? Because lensing is just a remarkable.
1:15:01 effect.
1:15:02 The photon interference reaches a maximum when there's no history.
1:15:06 A good principle. Remember, it doesn't matter if it interacts… it can interact with matter, but if it interacts with matter in a fashion that leaves no history.
1:15:15 then you can have a quantum effect. And that gives a lot of options for quantum effects at all sorts of scales.
1:15:22 All sorts of temperatures.
1:15:24 Next up will be Part 3, Photon-Electron… electron-Photon interactions.
1:15:29 That gets an easy part. I will…
1:15:32 try to do that in one session. That might… that might need to be broken down into a couple sessions also, but I think I can do it in one session. And there's the sign up for that, and with that, I am finished.

1:15:47 HM Thank you for the great talk, and I see Ron has some questions. Can you unmute?

1:15:57 RS No, I think the only question I posted was,
Can I see your fancy flashlight?

1:16:04 TB Unfortunately, I don't have it in my pocket at the moment.

1:16:09 RS hurry!

1:16:10 TB Yeah, I know, I know, it's their… it's, it's the, OLED, OLED…
I love their products. Here's… I can show you another product by the same company.
If you can see that. Now, the color's not showing up, it's just a little glowing LED sphere. They just make some great stuff, and it's, it's kind of costly, but it's a great little flashlight, and

Love, love that green laser. The green lasers are so, easy to see. I, I grew up with red lasers. We all had red lasers. I remember, first time I got a green laser, I went to a photo, I think it was a,
I don’t remember, it was one of the, spookiest spy, it was spy, it was a spy meeting. I thought, oh, I can show off my green laser. Everyone there had a green laser, so they just… everybody had to show off the new technology. At that time, it was new tech.
I’ll bring my, my, my laser package next time.

1:17:05 RS Yeah, the green laser caught my attention. Work I did with a quantum sensor.

1:17:11 RS requires a green light source at, I probably, I probably won’t have the number right, 526 nanometer?

1:17:21 TB No, no, I don’t… I’m not gonna remember the numbers. I do… I do remember the green…

1:17:26 RS I’m always on the lookout for a cheap, a very low-cost, solid-state green laser.

1:17:32 TB You mean a single-stage solid-state green laser?

1:17:35 RS Yeah.

1:17:36 TB I don’t know if those exist. I don’t… I… in fact, I was looking up just a couple days ago, and I could not verify. What they do is they get…
a… let me see if I can remember the steps. It’s really wild. They take an infrared laser, a deep red laser.
They activate another laser that gives a deep infrared that’s completely invisible.
And then they run that through a frequency doubler.
And after the frequency doubler, you get the green laser.
So, the process they do to create a green laser, I’m actually amazed they’ve gotten the cost down as much as they have.

1:18:13 RS Yeah, that’s…

1:18:14 TB There’s about 2 lasers and a frequency doubler.
In… in that arrangement, to get that green light, and yet it works quite well. I… I would love to see a direct… there may be some, but I don’t think… I think the ones commercially are…
Mostly… Okay.

1:18:29 RS Actually, you say that, now I wonder if the ones I’ve seen… the ones I’ve seen are very expensive.
And it may be for that reason, and they may not actually be a single solid-state element.
Yeah.

1:18:41 TB Yeah, and I looked it up, but I didn’t come to a clear conclusion whether they had
produced, you know, they’re limited by materials, you know, atoms are atoms.
And it’s just kind of luck of the draw of which atoms produce which frequencies well.

1:18:57 RS Yeah.
Also, I guess I put a comment in the…
chat about, as the crow flies. I… when I was in flight school, I heard that term all the time, so I wonder if it has its origins in aviation.
At the best case, it would be, you know, does anybody know if the Greeks understood point-to-point navigation?
on Great Circle routes.
That would probably be the first time they understood it.

1:19:27 TB Some of them, almost certainly did.

1:19:29 RS Mr. Greek song.

1:19:30 TB a large number of the Greeks did very much understand not only that the Earth was round, but they had a pretty good estimate of the size.
So much of that has been lost, so much of that has been lost, but what we have confirms very nicely that knowledgeable Greeks were very aware of it, and they had done some deep well measurements where they actually got a pretty good estimate of the radius.
So.

1:19:54 RS Yeah, I forget that guy’s name, the guy is famous for the experiment.

1:19:58 TB Yeah, yeah, but we’re interested in.

1:20:00 RS I probably had that wrong.

1:20:02 TB Sounds right, sounds right.
They, they have, their… their engineering acumen was just…
Much greater than we realize, but they tend to keep it in local schools.
apprentice-style model, so we just lost so much of that. But the Greeks were much more scientific than we give them credit for. We think they’re philosophers, but they experimented and they observed.
It’s just that we don’t have a good record of it.

1:20:33 RS Sounds good. So, bit of trivia in today’s technology.
Calculating great circle routes is done with the Haversine formulas.
Which are, it’s pure, pure trig, and, very accurate.
That’s what all aviation navigation stuff is based on.

1:20:58 TB Mercator projections give us such a distorted view of distances, especially in northern latitudes.
You know, you see the plane flights, and it looks like, why are they going so far north?
While they’re going in great circle, it’s actually the shortest path to that, so…
Mercator was good if you want to keep your compass pointed one direction, and that was invaluable for a lot of
The navigation of that time, but it’s not the most efficient, especially when you get up north.

1:21:26 RS Absolutely correct.

1:21:33 TB Questions, anyone?

1:21:36 HM I see Dr. Catino Penn. He put, the blue butterfly hasn’t gone pigmentation, but microscopic ridges that produce this
Fraction gradients, thus resulting in blue color.

1:21:51 TB Yes.

1:21:52 CP Yeah, just a, just a comment there to her about this, the blue.
Blue butterflies.
Which, which inspired metamaterials.
My… I just got… I got kind of speculation.
Terry, listen to your talk more.
On, on… Richard Feynman’s work.
I just wonder if… If photons do not exist as we think, I, just imagine…
A kind of multi-dimensional mesh.
A multi-dimensional mesh infinitesimally small.
Size, almost a Planck-size
overflossum.
Theoretically, and what we perceive as light is just an activation of this mesh.
At, at certain directions.

1:22:56 TB Well, when we… the observations that we see on photon activation
Usually, they take scale at a much larger… well, they do take scale at an enormously larger scale than the Planck scale.
That doesn’t preclude the idea there could be activations at a deeper level with that, but when a photon travels and hits an atom, the smallest resolution of the photon energy that is observable experimentally, is the size of that atom.
And actually for the same thing for the electron. We talk about the electrons, in an orbital.
The actual size that you can observe the electron in the orbital is the orbital.
Until you add more energy.

Now, when you add more energy, especially to an electron, it's harder with a photon, but you add more energy to it, you can make it, appear indefinitely small, presumably down to the Planck limit, although Planck limit would require too much energy to exist in our universe, as far as we know.
But you can shrink things down as far as you want by adding more energy. But observationally, you have these interesting limits, and that includes on photons. Photons are weird, too, because you have, like, a wavelength
That can be hundreds of times larger than an atom.
And yet, when the photon hits the atom.
All of that energy goes to that one electron… to one electron inside that atom.
So, you know, you're looking at it and go, how does… how does that work? But you don't… but you don't see scaling beyond that. You know, you're always limited by this, by the energy of that particular medium.
So, there can be, you know, there can be possibilities… the fact that you have an infinite limit
It makes it interesting, because you can, like I said, especially in electrons, you can always make it smaller.
And you can always make a photon
More precise in terms of how it navigates
objects by increasing the energy, like X-rays diffracting off of the gradients. But actually, you know, in that case, the X-ray bounces off the entire crystal.
It doesn't bounce off individual items, it can hit an individual atom.
But when it hits it, the minimum scale is that size.

1:25:08 CP Yeah, but what I'm speculating, it's not just the scaling.
I was speculating that That photons are… Like, being everywhere.
Been part of the mesh.
Universal mesh, everywhere.
So, you, you don't see, light or luminosity.
Without activation, so it's only when they are activating, they appear to occur.
But they… They exist.
In a state of, inactivation, that's what I, what I meant.

1:25:48 TB Okay.
Yeah, and I, I, I don't think that's that far away from,
Most versions of field theory are.

1:25:56 CP Yeah, exactly, yeah, it's a recreational field, yeah.

1:25:59 TB very productive field of physics on the activation energies, and I like the electron-positron pairs, those are…
Those are inverse activations. You get two waves with opposite… kind of spiraling in the opposite direction when you do that kind of activation. So there's a… there's an interesting little topology relationship on the field

theories with that. They're like solitons with opposite polarity. Put them back together and they disappear. They turn into something else.
So, yeah.

1:26:28 CP Yeah, thank you.

1:26:29 TB Thank you.
Other questions?

1:26:34 HM William has a question. Can we discuss electron longevity?
And he posts a lot of… Comments on the chat.

1:26:45 TB What was the phrase again? Electron…

1:26:49 HM Electron longevity.

1:26:52 TB Oh, the fact that electrons, you know, how long do they last?

1:26:56 HM Right.

1:27:00 TB Well, the simple answer is, as long as the universe exists, barring cancellation via a positron or some other phenomenon.
The electrons seem…
have no even theoretical trace of decomposition or breakdown of something else. You can cancel them. Again, you can always cancel. The antimatter can always cancel things out, but that's more like topology.
It's like saying, you know, two opposite springs, you put them together, you get a straight wire.
As long as the electron's there, there has been speculation about protons, being eventually
unstable over time. No proof of it. It's been a speculation, but those are much more complex particles. They have, you know, 3 quarks.
A lot of gluons, a lot of stuff going on in a proton.
But, longevity is extremely good for photons. At the end of the universe?
That's a good question.
you know, how does… how does the universe end? And then you get your answer about what happens to the electrons at that point.
Other questions?

1:28:20 HM But William, do you have some more things to discuss about the…
Electron longevity.

1:28:27 TB Yeah, if you had other questions on it, I'm not sure if I answered what you were really trying to get at.

1:28:39 RB That was the correct answer.
Definitely the correct answer.

1:28:44 HM Robert, I cannot hear you.

1:28:51 RB So, you can’t hear me?
Okay, okay, I simply said that,
That was the correct answer, that’s definitely the correct answer for electrons, and like you said about protons, those are at least theoretically, and I thought, actually, some… no, I guess not proton decay had been detected, but yeah, their composite particles can always have decayed,
Decay quantum states, and so therefore they can
Theoretically have a finite longevity, but,
Yeah, I guess, just like electrons are Pache, but electrons are visualized as being of indistinguishable size, basically infinitesimal size, I… I said that horrible word, they, they…
They seemingly also have infinite, infinite life, except for the effects that you had previously mentioned.

1:29:45 TB Yeah, and what’s fascinating is they’re also all absolutely identical, which…
You know, if you look at how things work in the classical world, you can’t make an identical copy of anything, but in the quantum world.
Electron is electron is electron, doesn’t matter when it was, or what part of the universe, what time in the universe.

1:30:04 RB It makes the phenomenon of entanglement rather fascinating, because, entanglement would seem to require non-identical particles. In other words, some sort of distinguishability. Am I entangled with this electron, or am I entangled with that electron, or that photon, or that other thing? Yet, we have the… yet in statistical… as you say, in statistical mechanics, quantum mechanics, we have the fundamental concept of identical particles.

1:30:29 TB And the… the identical part, it’s… it’s almost like a…
a virtual instantiation of something. The idea is that you have this package of properties of charge, of spin, of mass, and those are the ones that are just absolutely invariant. But then you have this larger issue of saying, yeah, but they’re not in the same place.
And the moment you say they’re not in the same place, they’re no longer identical.
So, the location itself is an instantiation of that single set of properties can be instantiated at different positions, and those different positions can have these relationships of entanglement.
So, yeah, the complexity builds around that, but what’s fascinating is where does that initial package
Of just utterly invariant properties, come from.
Wheeler speculated about this, his idea of a single electron going back and forth as a positron, electron. There’s no antimatter, not enough antimatter in the universe to do that, but… but he certainly worried about it. He thought it was a fascinating issue, and he thought it was

worthy of examination. Because again, classical world doesn't work that way. We don't make
We have to get down to the atomic and elemental level, then things start becoming absolutely invariant.
But, we have a hard time making exact duplicates. Things mutate a little bit over time.
So…
Other questions?

1:31:59 RB I was gonna say that, consider the no-hair theorem, which nobody can see me up here, but I have much more consideration for the no-hair theorem than, than Terry does, but, the,
The no-hair theorem I'm referring to is in classical general relativity, which makes black hole theory, which basically says that a black hole can be characterized completely and invariantly by its mass, its charge, and its spin.

1:32:27 TB Yes.

1:32:28 RB Not by accident, I think, replicates what Terry just said about quantum. The interesting thing is that more recent research has indicated that at a quantum field theory level, that's not true anymore.
Black holes can get some hair.
So the question is whether those invariances and whether that package of invariant properties survives from the classical world into the quantum world, or at least into the quantum field theoretical world, or somehow gravity special in that regard.

1:33:01 TB The history of, the…
nature of the event horizon, if you look at the history of it, it's just intriguing, in part because they keep changing it. It has changed over the decades. There's this idea that you couldn't have an electrical current of some sort going over. Then they kind of go, oops, well, no, actually, it's more complicated than that.
Event horizons are… you know, we got the major characteristics of black holes, but when we get to the details and the quantum level, wow, there's some interesting research still going on with that, and some interesting observations going on with that.
One of my favorites being that when a…
When a star goes into a black hole, it doesn't just fall straight in. It burps back out with a signal maybe 10 years later.
Now, that's… that's intriguing. So, that's… that's not what you expect. You think, you know, it falls in the black hole, and that's the end of it. And it's not that simple. The orbital mechanical and the angular momentum alone does not allow that kind of simplicity.
Every object has angular momentum, and when you get to a black hole, the angular momentum is intensified
just, I'd say astronomically, but that's an understatement in that case. And as a result, there's momentum issues that you have to deal with

that apparently are involved with the actual observations that we… that have been seen.

1:34:23 RB But nonetheless, the burp out you’re talking about, that does not actually come from the, quote, interior of the black hole inside the event horizon, right? That’s just an orbital mechanical, general relativistic phenomenon around the event horizon, but not back out.

1:34:40 TB But where it kind of fooled people is I think a lot of people, maybe even Kip Thorne, if you’d asked them before that, some of those observations, they would have said, yeah, it should go right on in.
And, the delay, the idea that 10 years later, it’s still…
showing a signal has not yet penetrated the event horizon, I think did surprise, surprise quite a few people, because you kind of think of this black hole as this irresistible force, and it is more complicated than that. Again, the angular momentum
issue, the momentum states that, ‘t Hooft has delved into that some.

1:35:16 RB We still don’t know a lot about black holes, even though we’re using them in particle… in particle physics and string theory and what have you. We, 40 years ago, no, more than 40, no, more than 40, almost getting on 50 years ago, I was tasked with trying to solve the care interior problem.
which is the solution of the Einstein equations.
for the case of a spinning black hole inside the black hole which has an actual fluid inside it, similar, analogous to the Schwarzschild interior solution for a static
not black hole, but a static star with a fluid inside. People forget that we talk about black holes all the time, people are more familiar with them than stars, but a Schwarzschild solution applies as much to a regular star as it does to a black hole, likewise with a Karen solution.
Unfortunately, I wasn’t able to solve that, I don’t think it’s been solved yet, but .

1:36:07 TB soundbite.

1:36:08 RB Alone early.

1:36:09 TB problem.
Did you do a paper on it?

1:36:12 RB Very hard one. The CARE exterior solution was a hard problem, and nobody, at least as of some decades ago, understood how care, in 1963, solved it.
It’s, you know, he kind of miraculously came up with this metric for the care exterior solution, published it in physical review letters, and nobody could figure out where it came from.

You can easily… not easily, but you can show that it's a true solution, because it solves the equations, but how he got it going forward without reverse engineering, nobody knew.

1:36:45 TB Did Kara ever talk about it? Did he ever give some interviews or anything about… How we got that?

1:36:54 RB No, I don't think he did. I think he… I think he died some time ago. He published, I think it was in 1963, and I know I did… I did my research around 1980, and at least as around… at that time, nobody knew… nobody really knew where it came from.

1:37:11 TB And that's not the only case of that. There's been some other interesting cases of physicists who just sort of solve something. Everybody look back at it and they go like.
how did he do that? There's one that… there's one that Feynman quotes, and I… I can't remember his name offhand, but Feynman showed a lot of respect to him and said that every time this guy says something that turns out to be right.
And, and, coming from Feynman especially, that's a remarkable statement. I wish I could remember the fellow's name. But, yeah, you get these interesting little…
Cases where somebody just comes up with something, you're like.
how do they do that? And, you know, it can be very… it can seem obvious after they do it, but…
Until they do, it is not so obvious at all.
So.

1:37:57 RB I tried, I tried solution generation methods, but, I couldn't,
I couldn't get very far with it.

1:38:04 TB Did you… did you publish anything on the… on the negative results? Did you… I'd love to see the paper if you've got a copy.
No, we didn't… we didn't do that, because I just didn't… didn't get… it wasn't… it wasn't so much theoretical in the sense that, it wasn't really a fundamental, it was just more of a mathematical thing. How do we do this? So, by that time, solution generation methods had just been started to be applied to exterior solutions.
But, trying to do it with an interior solution was new.
And, it just couldn't… and I was not really familiar with that kind of math. The guy I was working with was a… a postdoc, and he… he was… I mean, I was a… I was barely out of undergraduate back then, and he was…
a little bit familiar with it, but we just didn't get it. Actually, it's an irony of exigency, a physicist, a few months after I basically finished the research and had to get back to other non-physics things, a big tratisse got published.
on solution generation methods, if I had 5 authors on it, big, big fat book on that, and I just miss being able to see that. Now, maybe that would

have helped, I don’t know, but, the, it’s a well-known book now in general relativity, but, yeah, just to…
just the time of it, but that was, interesting. You know, solution generation methods in general are interesting, because it almost gets down to the point, to me, it always, it was a matter of what is physical and what is not. Basically, what happens is these solutions, these different solutions of the Einstein equations are actually related to each other.
group theoretically.
And you can actually generate new solutions from other… from existing solutions by group theoretical manipulations. I always wondered how… how physical was that? That’s a… those are mathematical… that’s a mathematical manipulation, but do they have any physical reality? You know, you can generate something… you can generate a solution with spin from something, a non-spin, or whatever. And that… that was always a fascinating… it actually,
it actually…
became a big branch of… some of a big branch of modern mathematics. It contributed a lot to nonlinear… nonlinear partial differential equations, chaos theory, and things like that eventually, but that was the actual origins of it in the late 60s and the 70s.

1:40:20 TB Do you remember any of the author names or the titles?

1:40:23 RB Yeah, I think,
I’m trying to remember here, there… I oughta remember, there are 5 of them. I might have it somewhere, I can… I can maybe find it and type it down somewhere, but.

1:40:37 TB Have you ever read any of ‘t Hooft’s antipodal papers?
On, on general… on general relativity?

1:40:45 RB Oh, you mean… Oh, you mean the particle physicist. I’ve heard of him, I don’t recall the antipodal papers.

1:40:53 TB Yeah, the, and it’s actually based on, oh, and I can’t remember her name either. She, this is… she had a, the idea, like, 20 years earlier, and, to Hooft.
expanded on it, but it was, and that gets into some of the momentum issues I was talking about.

1:41:11 RB Someone like, would that be one of the… was that, perhaps one of the DeWitts,
Is she part of it?

1:41:18 TB My department…

1:41:19 RB email, mathematics.

1:41:20 TB It’s terrible. I always… I always like it when I hear the original author of an idea.
And sometimes the ferret… and that was the case where I made sure to ferret it out myself. And then I go and I forget the name. And I just… that bugs me. I’ve never been that good with names, but it bugs me. That I, I forget the name, but… but the antipodal is, is interesting because it’s a different take from some of, ‘t Hooft’s, earlier work.
And, again, I think the focus on angular momentum,
Yeah, it has to be Persian.

1:41:55 RB Where then?

1:41:56 TB Yeah.

1:41:57 RB And, yeah, I don’t smell that same…

1:42:00 TB And you are right that I do believe the Department of General Relativity has some interesting new turf, is the idea that if special relativity is meaningless outside of measurements of matter, which I very strongly believe that, and I can point it to Einstein. Einstein was the guy who came up with it. I mean, he’s very clear about it in his 1911 paper, where he predicted the twin paradox.
That’s how he predicted the twin paradox, was that he tied everything down to actual clocks in the different inertial frames, including procedures that we would call initialization procedures.
For defining the state of those clocks.
And you look at this stuff, and it’s so different from the simple mathematical extractions that we use these days.
that you gotta wonder is that there’s gotta be some more analytical power to getting deeper into that model. But Einstein himself switched over to Minkowski simplification after that, and never explored that anymore. He stood by it, he predicted something that nobody expected, which was that time dilation is very real.
And at that time, that was considered a pretty crazy idea.
Even for Einstein. So, and of course, this goes back to, my, firm position that
Standard relativity is hierarchical, it’s… It is embedded.
The idea that you have an inertial frame that is completely isolated from other inertial frames in the universe is just not true. A relativistic train on a train track is still in the same frame as the train track.
It still can be measured. It can be measured up close, down to the atomic level in principle.
And it still gives clock results and still gives the answers. If we treat inertial frames as each one is a separate universe in itself.
We’re not getting the proper connectivity in our relativistic theory, at special relativity level.
And I don’t know what the implications are that… for the gravitational theory, but it’s got to be something. It’s got to have some kind of an impact, that if you can’t…

If, if, if your, your, your structure…
Of special relativistic inertial frames in the universe is too simple.
And I would say that most of them are. It's a hierarchy. It's a hierarchy, and that alone is just fascinating.
a multi-scale hierarchy, that's gotta affect general relativity, but I don't know how. It's not something I've tried to look at. At some point, I would like to get into that.
But the smooth equation of general relativity, immediately do not address that fractal structure.
So, you can say, like, well, it doesn't matter, you know, we're just looking at spacetime itself. It says, well, but…
You gotta keep going back to that point. If you can't measure it.
Then it becomes a math calculation and not a physical theory, because if your math calculation has no correlation to anything in the physical universe.
Then you've got some difficulties in terms of what the meaning is.
So… yeah.
Interesting.
Interesting areas.
Any other questions? It's 1:50

1:45:13 CP A short comment there about,
The topic of unfortunate is about the clocking.
invisibility… So there's been so much work on clocking, using magnetic metamaterials to bend light and produce invisibility.
However, I think the problem is to do with, is the human face.
They're still struggling to hide human face.
She's using these metal materials.
Through bending or flight.
This is just a comment, yeah.

1:45:53 TB Bill, there's some interesting, interesting,
Interesting work going on metamaterials and how they could use those in that.
I remember in, oh gosh, long time ago.
The simplest way, in principle, to get an invisibility, Cloak around you.
is to use fiber optics. You use spherical lenses in an array, a detailed array, on the surface. You do 180 twists.
of the fiber optic cable, then you broadcast out the spherical Sphere on the other side.
And in principle, obviously you've got to get a lot of dimming, but in principle, you could create an invisibility cloak just doing that.
Completely classical.
Obviously, it's going to be grainy and all sorts of things, but I was always… I was just fascinated by the fact that a combination of spherical lenses and fiber optic cable bundles
can give you a limited form of invisibility without using any kind of exotic materials, unless you call the fiber optics themselves exotic.

The lenses have to be a special type. You have to have a graduated index on the interior.
This is stuff I used to chew in high school. I…

1:47:08 CP Yeah, it's very, it's very.

1:47:09 TB I had some weird hobbies in high school, so… and that was one of them.
Three-dimensional photography absolutely fascinated me. Three-dimensional photography using spherical gradient index.
lenses. And how I got onto that when I was in high school, I didn't… there was nobody I could talk to about that in high school, so it was just something I had fun with.
But it would… it does work, in principle. I've always…
Thought it would be fun to expand on that.
yeah, metamaterials are a fascinating topic these days. Any other questions?
Do you have a question about… The, electron longevity?

1:47:52 TB Okay.
Another question about longevity?

1:47:56 HM Question, comment? William?
Yeah, we talked about the electron longevity already, and yes, please unmute, yes, and ask.

1:48:11 WS Oh, okay. I get it. Thanks.

1:48:20 TB Did you have a question, Bill?

1:48:22 WS I had a, malfunction.
My machine crashed, and so I lost the previous,
transcript there, and I apologize, but…
I was so fascinated with your discussion of photons in this lecture, I just thought I'd…
Bring up a factoid about,
The longevity of, electrons that came up in a discussion this past week.
And, I just find the whole thing fascinating.
I didn't think about it that much until I saw it this week.

1:48:59 TB Hmm.
Was… was there some kind of discussion about a particular angle on photon longevity? Because I think… I have the feeling I'm missing something that was part of… that was the root of that question.
Earlier about longevity.

1:49:12 WS Well… I, I was, I…
You know, if you… if you get kind of philosophical, and you understand physics and

And, life and stuff, you know, you start to fixate on things like, well, the average,
Human lifespan is something like 2.2 to 2.6.
Giga-seconds and stuff, and then… And then, when you think about things like electrons.
Having such an incredibly, long lifespan, then it kind of freaks you out, because,
You know, our whole society runs on electrons.
And, and so, you know, you don't think of electrons
practically being the age of the universe.

1:50:04 TB And yet they seem to be, yes.

1:50:06 WS Right.

1:50:07 TB I'll tell you one that is interesting that's going on right now on theoretical side, which is neutron longevity.
There is a quandary going on about whether neutrons… when neutrons
Decay is measured by one method, they give one result, and where they're measured by another method, they give another result.
And people are seriously wondering whether there's some kind of a transformation going on where neutrons are converting into antimatter or doing something really strange. Wow. So, so it's not electrons, but there's a fascinating, ongoing experimental debate about the nature of neutron decay.
And also, I'm going to give one other answer. This is where I jump into all of my…
you know, other things, because this is a Feynman lecture, so I'm trying to focus on the Feynman thing. But, how long does an electron last? about…
60 billion years, and then it disappears.
How did I answer? Where did I get that? Because I am a dual universe person who believes there is a negative energy universe, and that we are currently in the process of folding around
And we'll eventually hit.
And instead of the big, big, crunch, You'll get the big foof.
And literally what will happen at that point is then you get a Penrose cycle.
that the electrons… and when you wrote… there's two kinds of anti-electrons. There's positive energy electrons, there's negative energy electrons, and they have a different dynamic. They both involve the left and right hands.
In our universe, the left-handed electrons dominate. The right-hand electrons are still there, they're absolutely part of the equation.
But the predominance, the excess, is of the right-handed version of the electrons. The other universe, it's the left-handed electrons. When those two get together.
it goes poof. And the reason I say 60 million is because, based on the expansion of the universe right now, this is actually in some of my earlier

presentations, a good argument could be made that we’re about a quarter of the way
somewhere… so it may be less than that, maybe more like 30 billion years. But I actually think there’s a good chance that the universe will simply,
kind of go bye-bye. In that case, electrons last maybe… 30 billion years. So…
But that is… that’s the out-there stuff. That’s the… you have to accept the whole dual universe premise, you have to accept the premise that the non…
Weak… the weak, blind versions
of the chirality of the fermions have negative mass, which I… is a prediction I absolutely make.
I don’t know if anybody will ever test it, and I think it’s probably testable, and I absolutely predict that. You know, half the fermions we know have negative mass.
And the reason we don’t notice it is because we have preponderance of the positive mass ones, that’s all it is.
So, we don’t see that, because it’s a very transparent interaction that we call the Higgs interaction, where they go back wiggling through time.
All right, that was… that was going out on the wilder end. So, thanks, Bill. Anybody else?

1:53:23 HM I want to say another mind-bending section. Thank you, Terry.

1:53:27 TB Okay, thank you.
It’s good to see everybody again. Always, and enjoy everybody’s conversations.
And thank you, Helen, for.

1:53:34 RB Thank you.

1:53:35 TB Boy, you’re doing double duty today, Helen. Thank you. This is, we really appreciate your efforts on all this. That’s fantastic.

1:53:44 HM You’re welcome.

1:53:45 TB Okay.

1:53:46 RB You’re the marathoner of, of physics conference hosts.

1:53:51 TB Yes, yes, Ethan.
So, see folks next month, I guess?

1:53:58 WS Hey, Terry, Terry, real quick before we, drop off,
I wanted to remind everybody, probably 4,000 or 5,000
people are gonna participate in that Caltech Quantum engineering workshop.

1:54:12 TB Yes.

1:54:13 WS Yeah, don’t miss that.

1:54:15 TB No, I’m signed up, signed up.

1:54:16 WS Yeah, I am too, and to me, that’s a once-in-a-lifetime thing, and they’re gonna have 16 quantum
PhDs, lecturers, so, I’ll be on the edge of my seat.

1:54:29 TB someone was kind enough to send a direct email to some of us in this group, and I responded, and they were kind enough to say, you know, glad…
Glad to see you there. So, we managed to get their attention, so, it’s nice that they are making sure to include us in that. So, I was very pleased to see that. So, yeah, that should be fun. That should be fun.

1:54:50 RS Yeah, I, doubled down on the Caltech thing. I’ve attended all of them, I think, since the beginning, and they do some great presentations.
It’s a… it’s a full-day thing, so…
You do it virtually, you can kind of tune out the stuff you’re not interested in, but, they, have done, for the last
3 years, at least, I think. They’ve done a good job, so… Highly recommend.

1:55:19 WS And, and, Terry, Caltech is where, Feynman .

1:55:23 TB Yes.

1:55:24 WS I started and ended his teaching career, I think.

1:55:27 TB Yeah.
Yep.
I love the fact that his lectures are online, and you know, if you’ve ever read his book, you should really listen to some of his lectures, because his style, he’s just…
It’s just a lot of fun to listen to them. And also, you do get insights that you… you don’t get from the lectures. There’s some very specific things where I’m going, like, what Feynman said.
Was actually a little different from what’s recorded in the book.
Sure. And you look at it carefully and say, and it was different because he meant it.
And that’s what… that’s what’s… you gotta really be careful what Feynman says about things, because he usually says… says things that sound a little odd, but he meant them to sound exactly that way, and it can be a little… can fool you sometimes, so… but it’s just great stuff, and those… those, again, these QED lectures are also online.

1:56:17 WS I tell people, if you really want to unlock Feynman.

Look up Ralph Layton, who was one of his, proteges and best friends, because,
He wrote books like Tuva or Bust.
And admittedly, Ralph Layton may have been the guy in the world that understood him the best.

1:56:37 TB A fellow named, I think, Laurie Brown is his name, I think his first name, last name, Brown. He's got a marvelous compendium of Feynman's works.
Including his PhD thesis and his later work.
And, I remember going through that. There's this remarkable transition that Feynman made between his PhD thesis and QED.
Which is, he stopped having photons hit electro- atoms, and he started having photons hit electrons.
And that difference turns out to be critical for understanding how we formulated QED.
Because the… the direct absorption of an electron… of photon by electron, technically.
is impossible, so… which is why, in his thesis, he had an atom do it. But then he realized, no, it's not impossible when you delve fully into the virtual world. It's just that it cannot persist classically. It has a finite lifetime.
So, yeah, great book, and if you want to get into detail with the Feynman's papers, Brown's book is good.
Okay, are we alright?

1:57:52 HM So, if there are no more questions, our next event will be on June 6th, Sunday, 10 a.m., with Dr. G. It's about quantum machine learning.
See you all there.
Thank you.