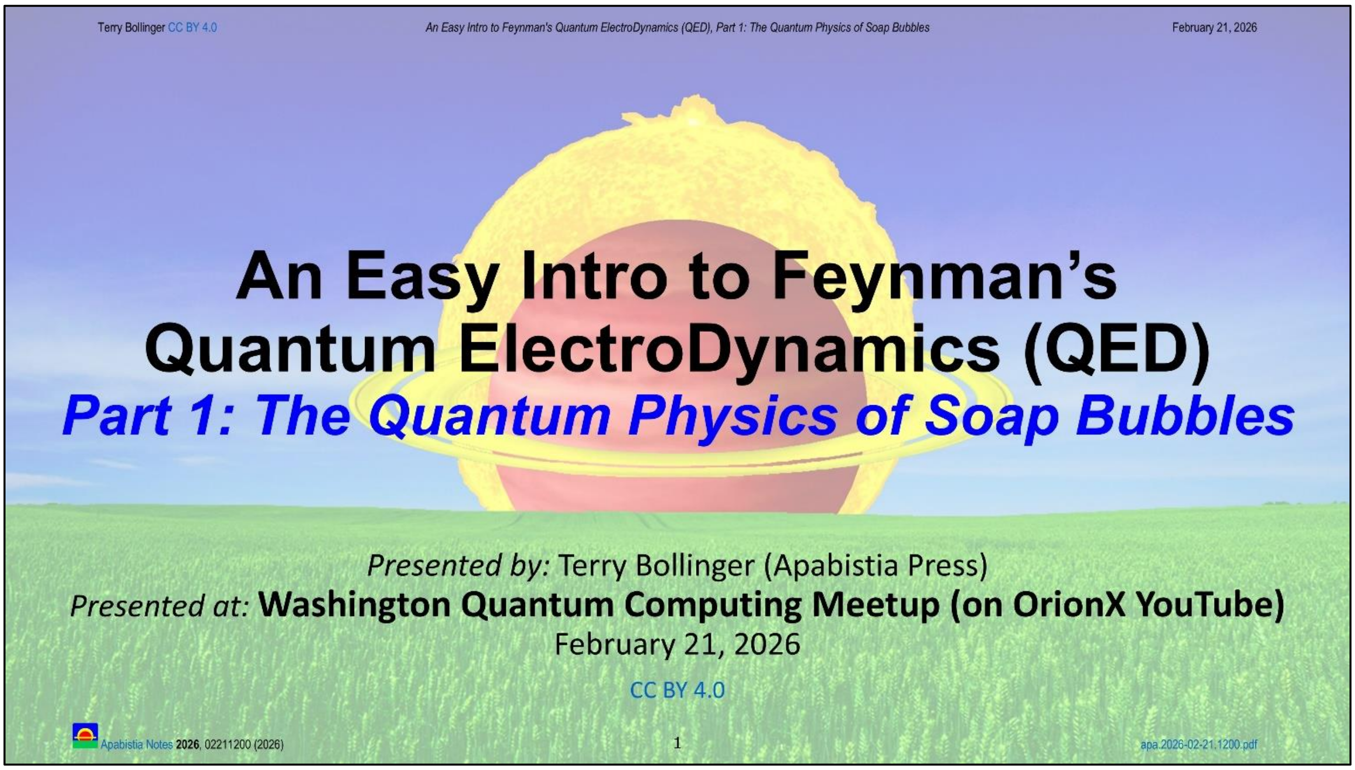
# An Easy Intro to Feynman's Quantum ElectroDynamics (QED)
## Part 1: The Quantum Physics of Soap Bubbles
(Edited Transcript)

Terry Bollinger
Presented at: Washington Quantum Computing Meetup (on OrionX YouTube)
2026-02-22.12:00 EST

**This is the edited YouTube transcript. You can view the full video at https://youtu.be/ICGbvh0s2sI**




00:12 **Helen Ma**, Team OrionX (HM): Good morning, good afternoon, everyone, and welcome to our February event with Terry. Terry, this is all yours!

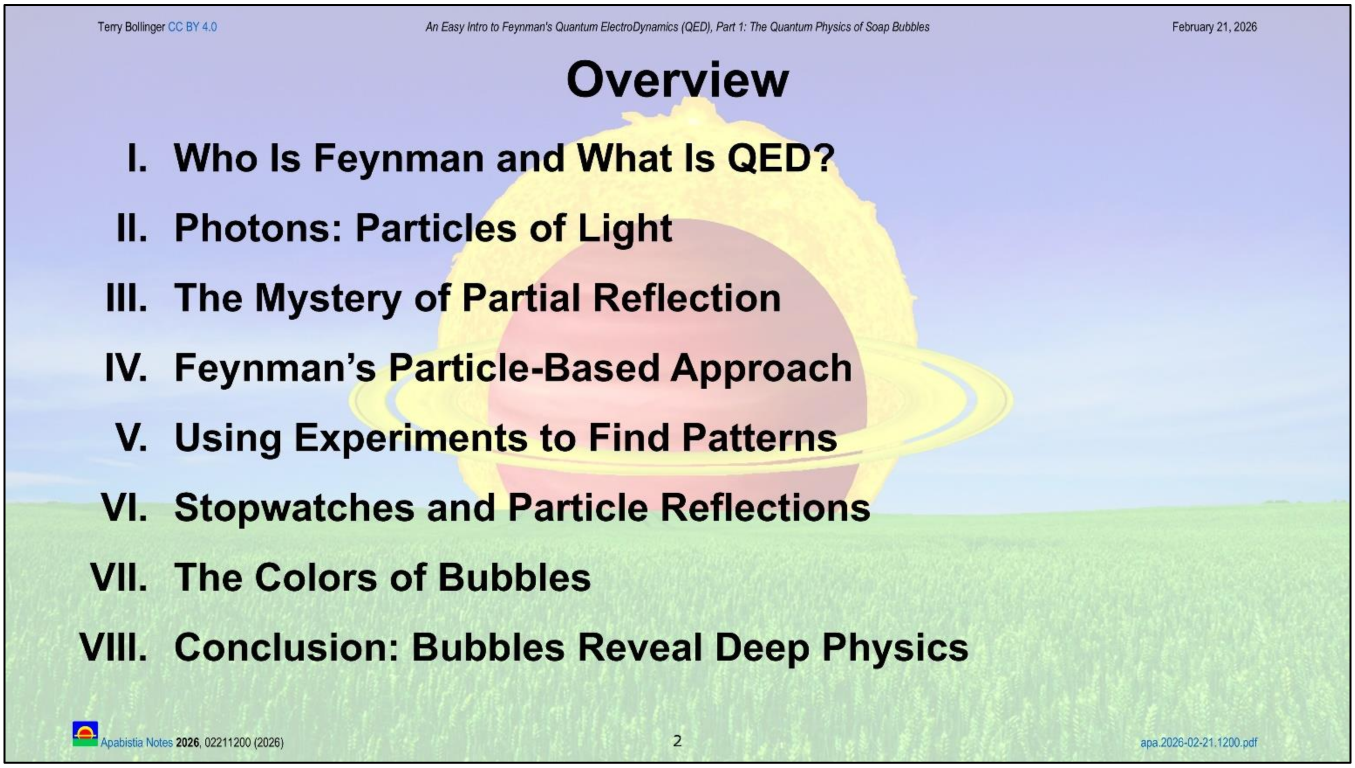
00:19 **Terry Bollinger** (TB): Thank you, Helen. This is a topic that I *thoroughly* enjoy. One of my favorite books of all time is a book called *QED: The Strange Theory of Light and Matter*. It was written by Richard Feynman, a famous physicist.

The delightful thing about this book is that he had a goal, and the goal was this: He wanted to explain to some of his friends *how he understood physics* — how he got his Nobel Laureate status — and he wanted to do it *without* using math! His idea was this: He didn't want to make people have to *calculate* the results. He wanted to show how the results — how the calculations — *came from the logic*.

So, it was an *intriguing* approach, and it was a *difficult* approach. It's not something you could do to just everything. But Feynman realized that he could, *in this case*, come up with some fairly straightforward representations that people could understand.

Now, the actual calculations — and getting those calculations to work *efficiently*, and applying them to *large problems* — those are much bigger issues. His point was simpler. He was saying that the *basics*, the *operations* from which everything *emerges*, have a simplicity to them that needs to be *known*, that needs to be *talked about*.

And that's what his goal was: To do this.

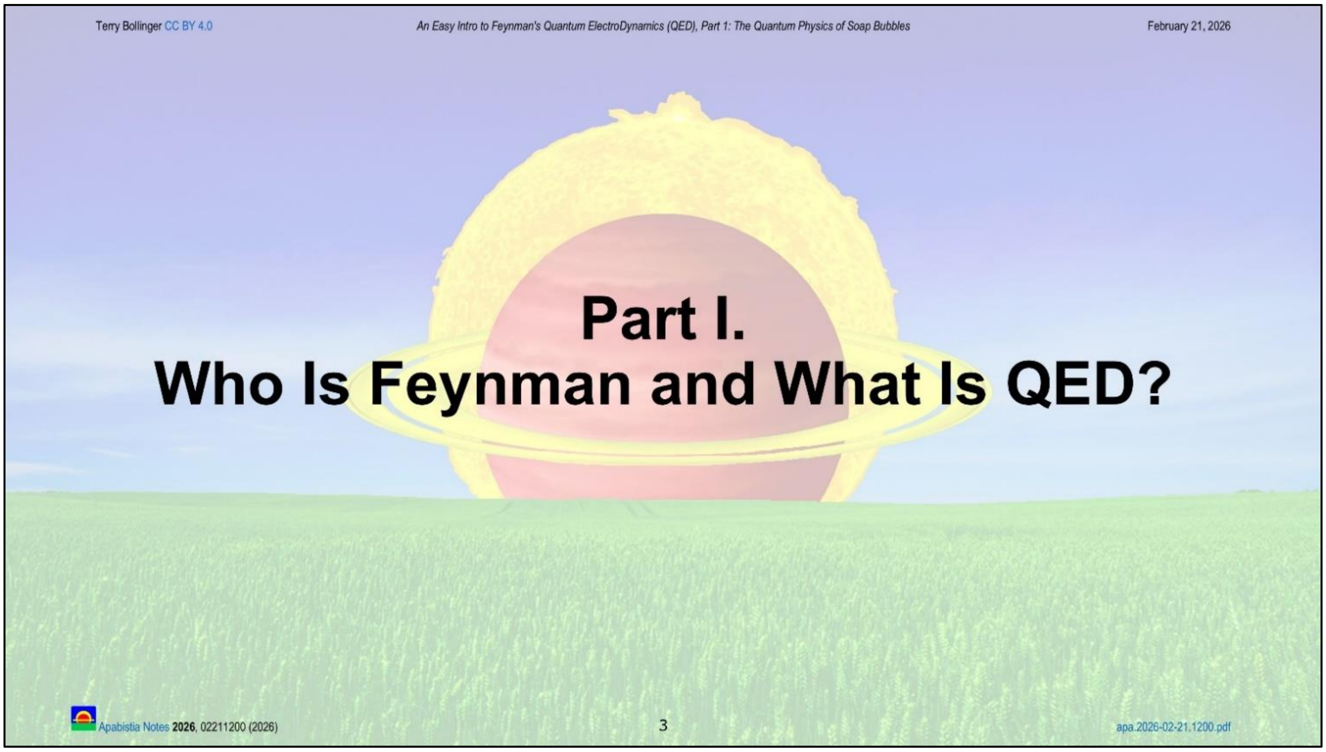



01:40 I've got eight parts to this presentation. Originally, I was trying, *very unrealistically*, to cover the whole book quickly! But there's too much that needs to be covered on these basics. So, I just went through the part where we get through the interference effects with soap bubbles, which is the first one or two sections of the book, which began as a series of lectures in New Zealand.

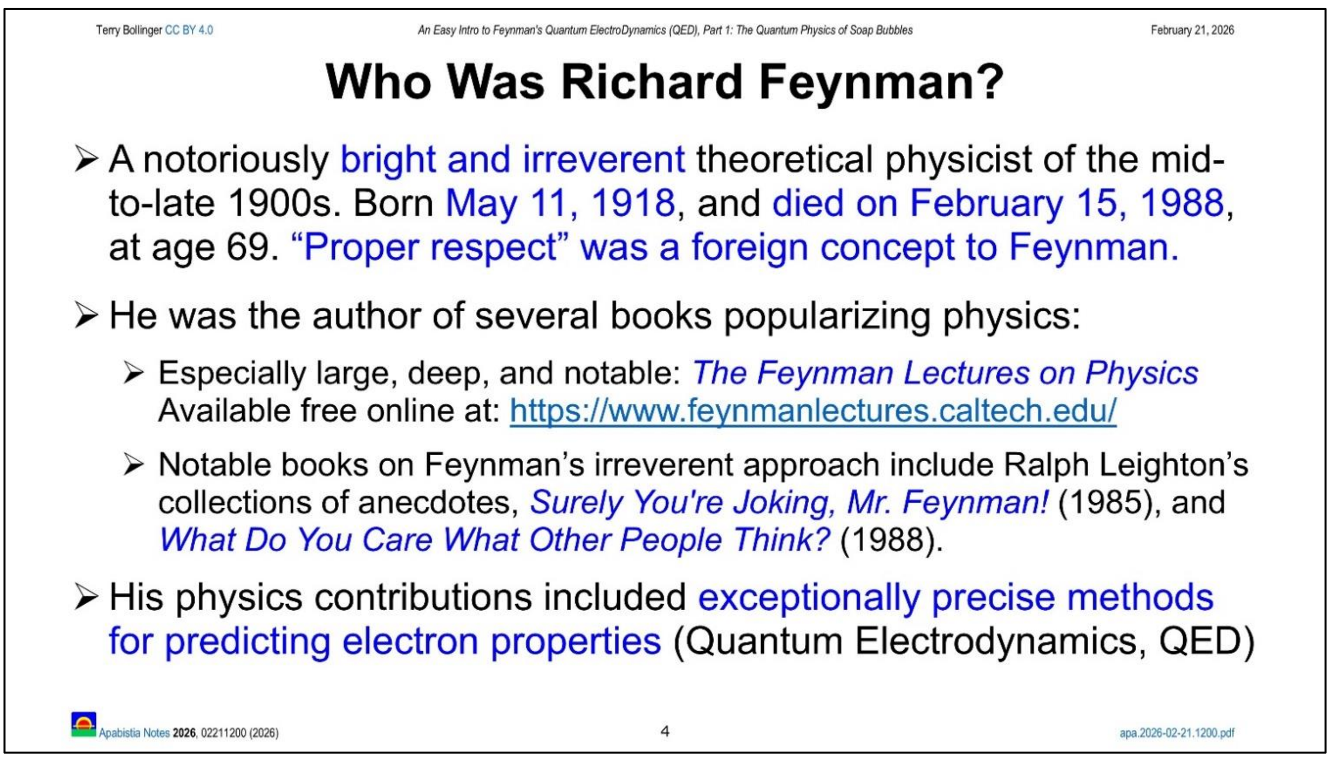
So, you can see the outline here, including "Who was Feynman?", to give a little bit of background in case you're not already familiar with him.

And his whole book is about *photons* — photons and *electrons*. What I'll be covering today is only about the *photon* part, to give a realistic coverage of that.

For today: Colors — the colors of bubbles! A *remarkable* number of things are covered by the color of bubbles!




2:32 Who is Feynman, and what is QED?




02:34 Feynman was *notoriously* irreverent. If you wanted Feynman to *disrespect* you, it was very easy. All you had to do was tell him, "*You need to respect me!*" And (chuckle), *instantaneously*, you would be at the *bottom* of his list of people he ever listened to again!

This was just an *inherent characteristic* of Feynman, probably something to do with his background, how he was raised, and his family. His dad was a tailor when he was young. Feynman considered himself an *ordinary* person who had unusual interests. He was *not* big on pomp, show, and a number of other things, and he very nearly declined getting his Nobel Prize.

It *wasn't* that he didn't like attention. He was *fine* with fame. He had no problem at all with being entertaining and being known by people. But he was just uncertain about whether a Nobel Prize was a good idea. And in some ways, he even regretted it later, because it *redirected* him away from his research.

So, in addition to *QED*, you can also easily get a copy of *The Feynman Lectures on Physics*, which are an *amazing* set of three books that cover just about every aspect of physics you can imagine. His *Lectures* were supposed to be an introductory course, but they covered so much that, to this day, people look at it for (chuckle) *far more* than just the freshman year of physics! They cover a *lot.*

And there are all these fascinating details! I love going through the Lectures, because I'll find things that I never noticed before. I look at some paragraph, and say, "I didn't realize he had *said* that. I didn't realize he had *looked at it* that way!" Or, "I didn't realize he had that *unique perspective* that he puts on this particular problem!"

So, there are lots of little *goodies* and *finds* in there. They are a *very good* set of books that are *online!* You can get them in their *entirety* online, without any charge. So, that's *great!*

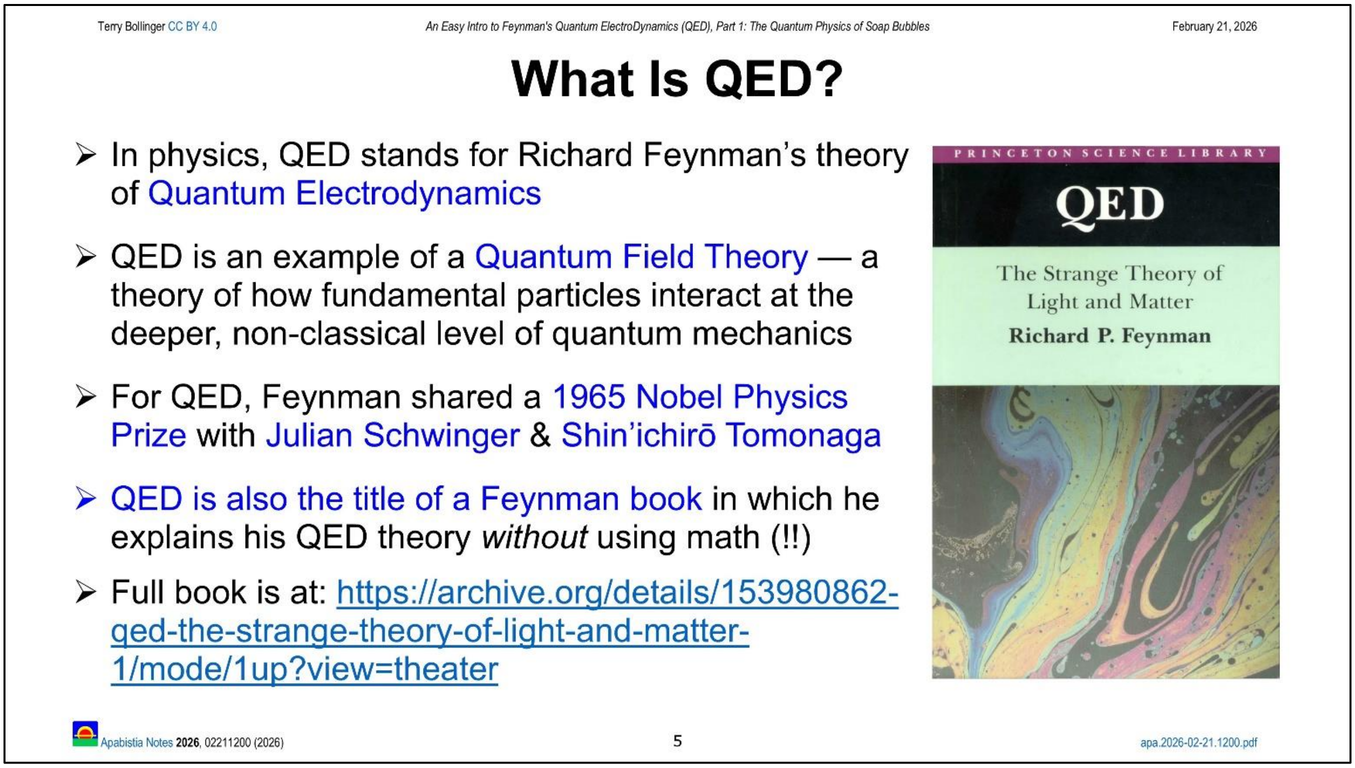
He also had some books that had been written about him. A particularly famous one, *Surely You're Joking, Mr. Feynman*, captures his irreverence very nicely. There's (chuckle) one part where he went on a long road trip with a well-known physicist, whose name I admit I forget at the moment, and their own descriptions of their own trip were just *strikingly* different. The other fellow was saying, "It was so great to go on a trip with this great mind!", while Feynman just talked about amusing little anecdotes on the trip. He did *not* consider what he had said to be all that relevant.

Much later, he also made a joke about his own QED theory in front of a bunch of Princeton mathematicians, and he *played his own theory for a laugh*. He said, "Yeah, it's probably all wrong. Probably it's just something like checkers."

But how many Nobel laureates do you know who would *make fun of their own work* in front of a crowd of mathematicians to get a laugh? And he *meant* it! He just said, "Yeah, it's probably wrong." His point was that while the *details* of what he calculated were right, we still don't understand what's really *going on*.

The particular theory for which he got a Nobel Prize is called Quantum Electrodynamics. Big name, nicely abbreviated to QED — which has nothing to do with the mathematical use of the word QED. But it is a way, in a nutshell, of describing electrons and photons — photons being particles of light. These are the two particles that we most often encounter in nature, because we don't see the nuclei of atoms; we just see the electrons.

So, those two particles cover a *lot* of turf.



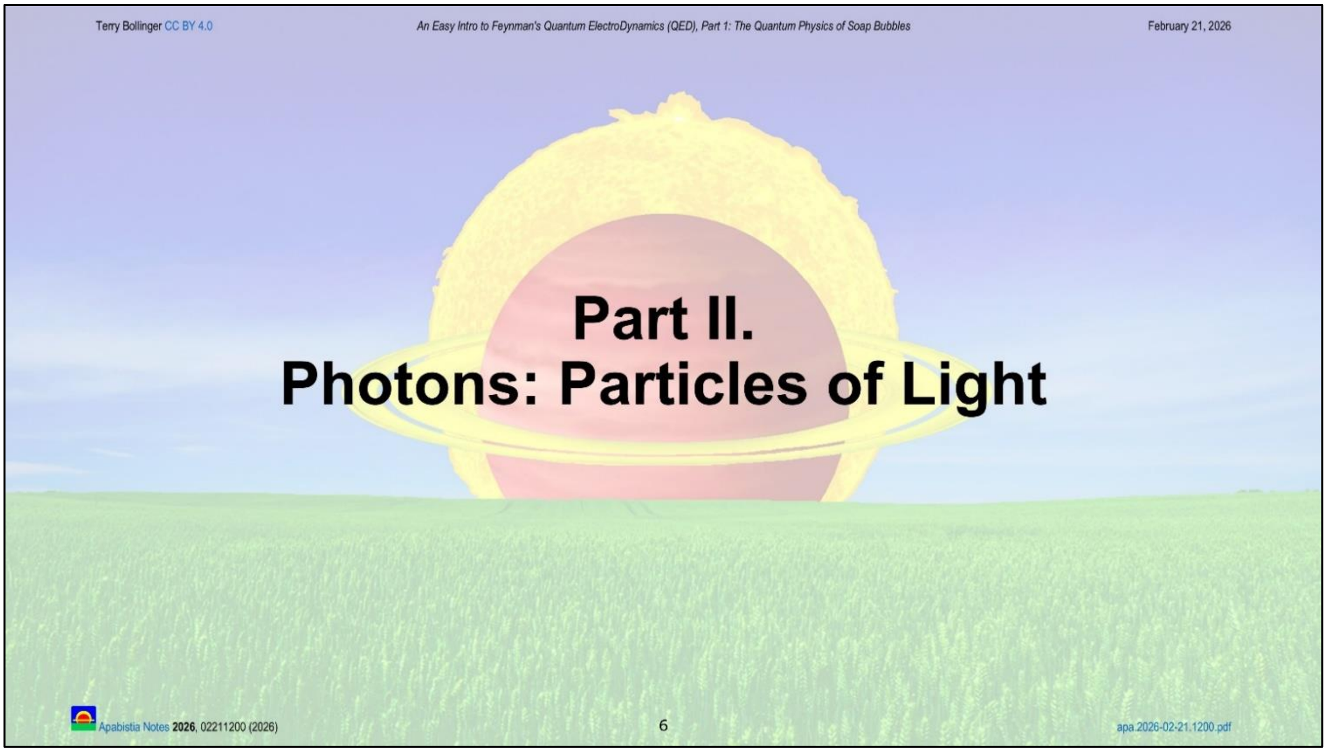

06:18 QED itself is an example of what's called a *quantum field theory*. There's a *marvelous* irony in this! That's because the premise that Feynman started with was that everything is *particles* — not fields.

You hear about the particle-field — particle-wave — duality, but Feynman had a *very unusual* take on this. A lot of times, people don't point this out — but it's worth pointing out! He started from the *other end*. He said, "What if it's all *particles*? What if it's just *particles*, and we don't really *have* a field?"

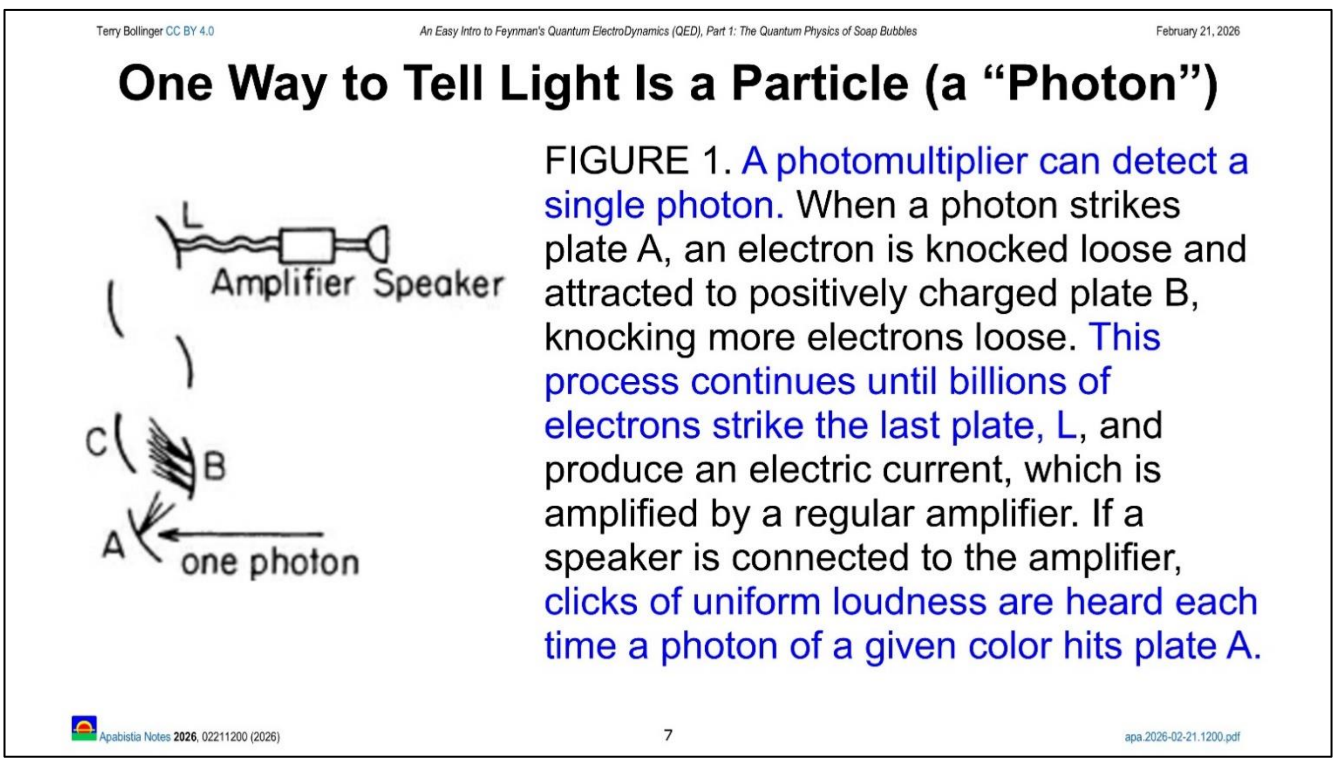
Now, at the same time, he had *no* problem embracing field theory. He had *no* problem working with fields. He used them in the math, and he was *extremely pragmatic* about that. But when he was trying to poke at something and say, "What's really, really, really, *really* going on at the *deepest level*?" — then he would back off. He would say, "Let's see if we can make it even simpler! Let's just dispense with the fields and have just the particles."

And that was a pretty radical concept. In fact, it was so radical that most of his fellow physicists did not understand it at all at that time.

As for the first edition book shown in this image, you can find it on the Internet Archive. The first edition is a marvelous thing. It has this beautiful front-cover picture, which you see over here on the right, of an oil film. The oil film has the same kinds of colors you see in a soap bubble. So that's on the cover of the first edition book, and it's a good resource that you can find online. There are also less colorful versions of it that you can buy online from any number of sources. If you get those, you can get the more recent intros. This first edition has only the original intros and the original preface.




[08:00] Photons! Particles of light! (Then, I make a strange throat noise I cannot explain! :)

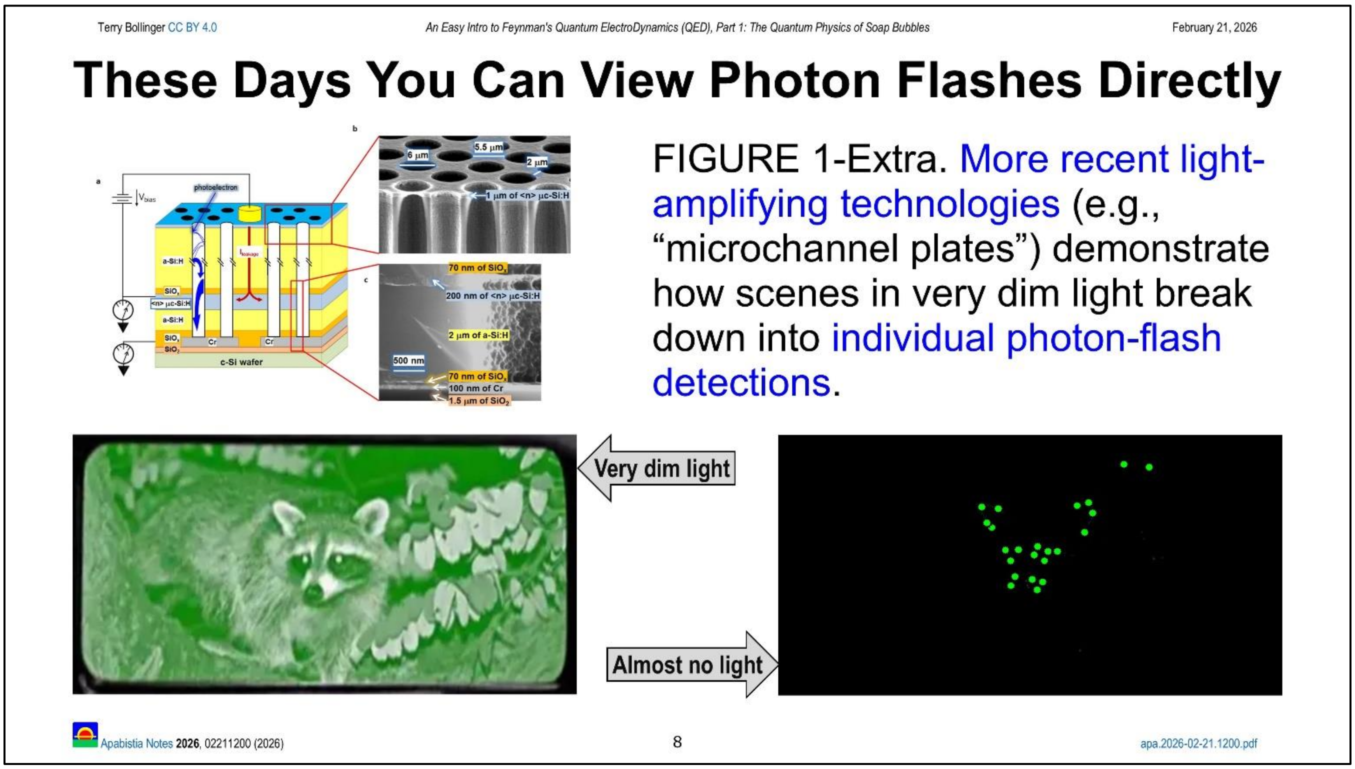



[08:05] *Why* do we think that light is a *particle*?

Because our technology *tells us* it's a particle!

You can go into a device, like a photomultiplier, something invented back in the 1900s, and you can have *one photon*, one *tiny little bit of light* going into it, and it causes an avalanche-type reaction. The one photon releases a couple of electrons, the electrons release more electrons, and back and forth it goes. So, you see, the avalanche just crawls up through here, in this column. At the end of that, in Feynman's time — back in the 1950s and 60s — this would have been sent to a speaker, so you would hear a *pulse*. You'd hear, like, a little *snap*, "toot!", and know that you just got a photon.

It is a remarkable thing that when you make the light very dim, you *can't get away from this effect*. You just keep winding up and saying, like, "Oh, below a certain point, there's just *nothing*! But up to that point, I get a number of photons that, remarkably, is just proportional to the energy that I'm putting into it. So, it's like the energy kind of gets grabbed into a little bundle, and then it pops out.




09:20 You can see these things directly these days. You can go out and buy equipment right now. You can go on the internet right now and find some devices where you can watch this yourself.

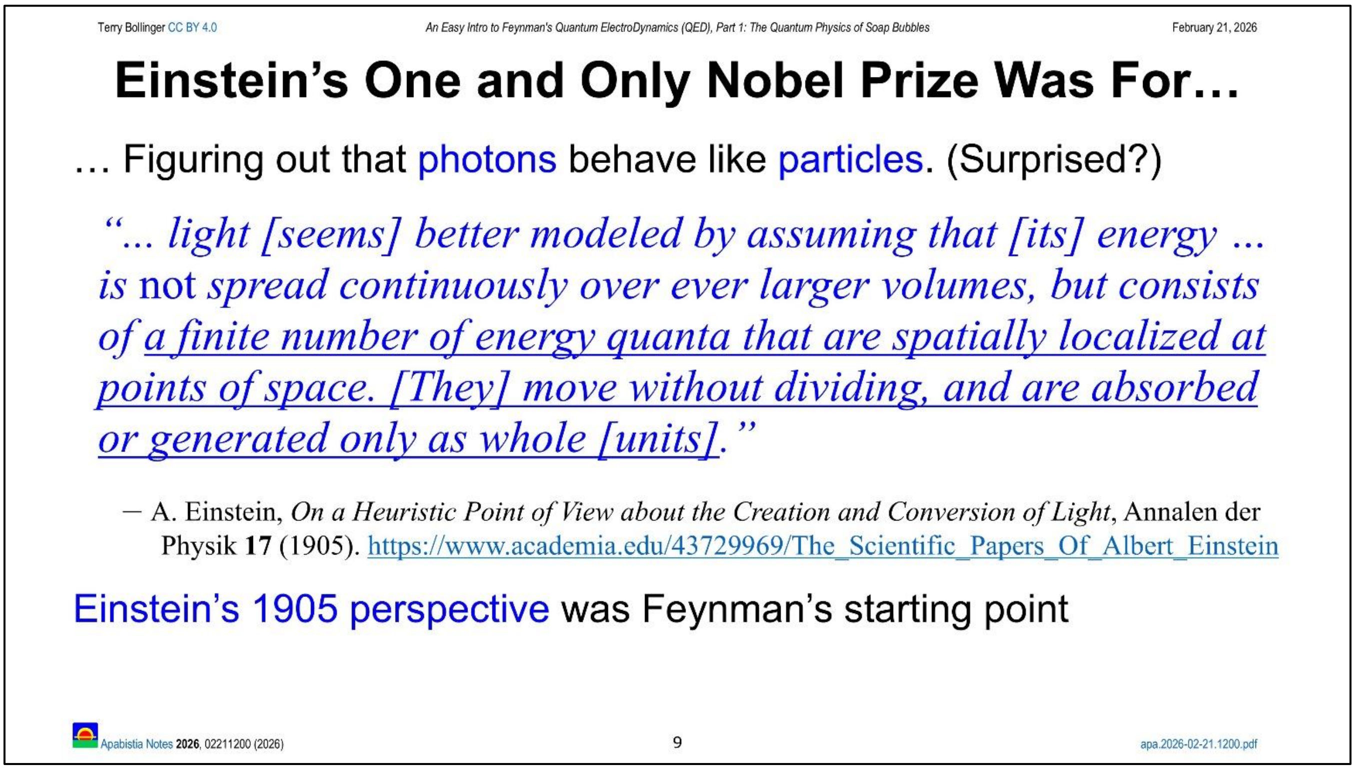
This is an actual little picture, an amplified light picture, of a raccoon in the dark. That's under very dim light, but if you go even *less* with the same device. What happens eventually is you get this little sparkly effect. You start seeing little bright points of light. See the little ears, see the little raccoon ears there? That is actually light images coming from this guy. So the photons are *so few* and *so far in between* that you can just barely get that.

The technology is essentially the same as what Feynman described. This device was not available at that time, but these little channels just have those same little avalanches of electrons going back and forth and back and forth, and then instead of hitting an audio connection, they wind up on a photo connection, where they produce a little flash of light. So, the same technology, but it's been turned into night vision goggles. And, it's a very useful technology to have. It's one that's commercially available, so you can find it out there. But it's just *remarkable*, because if you want to do this experiment, you can do it at home!

Even human eyes — this has been found out statistically — we can see photons! We can't see them well, and they're kind of like the subconscious level. We can't quite get them to where you say, oh yeah, that's exactly where it was. But if you do a statistical analysis of people in *extremely* dim light, it turns out humans *do* statistically detect photons! We can say, "Yeah, there was one right then… and there was another one then…"

So, even human eyes, when they're trained for it, and we've been in the dark for a while, can potentially see these little flashes. Photons, light, *always* come in flashes!

And isn't that *remarkable*? Because we don't think of light that way! I know everybody hears the word "photons." But to imagine light as being these little particles takes some stretching, and that's what I'll be getting into in this.




11:16 The interesting thing about photons — and again, I'm not sure why this isn't emphasized more, because I think it's just *fascinating* — is the idea that photons are "particles, period," did *not* come from Feynman. It came from a fellow named Einstein.

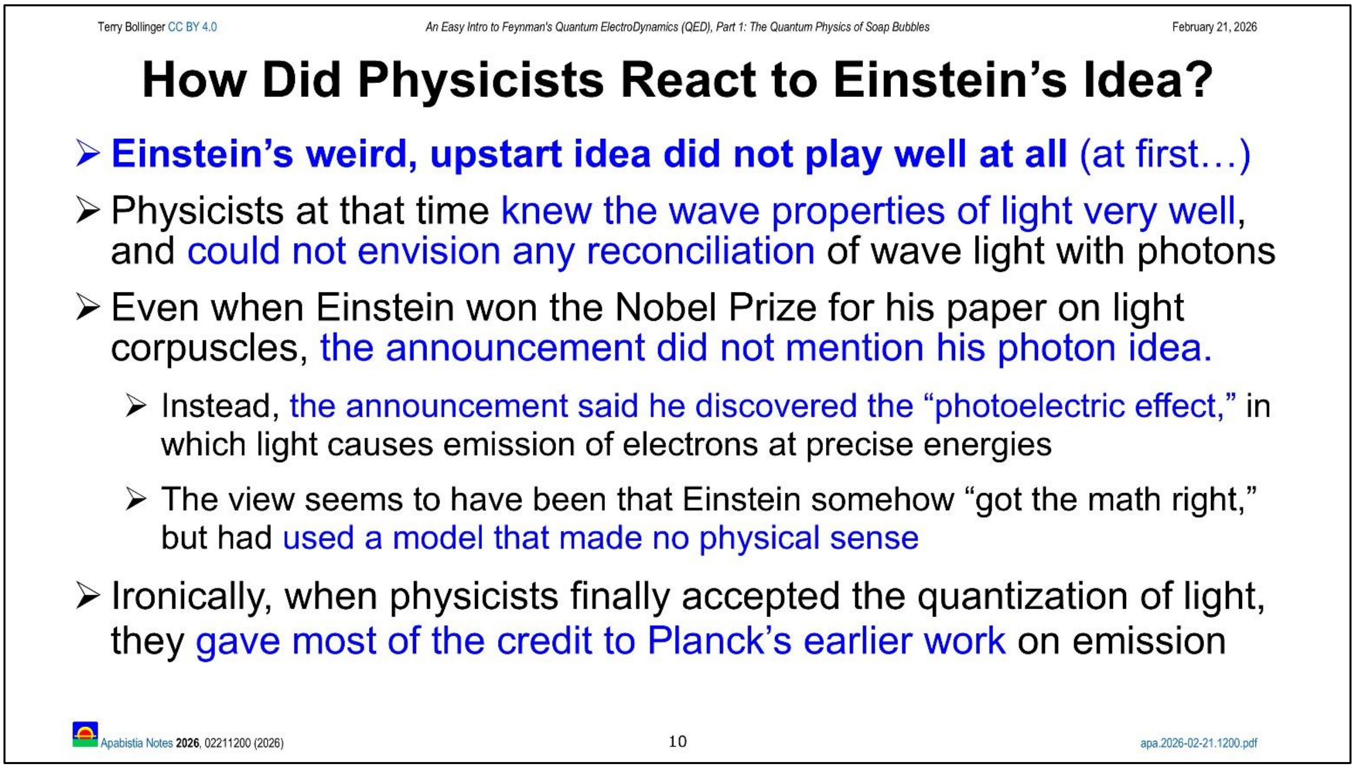
And not only did it come from Einstein, but it's the *only thing* he ever got a Nobel Prize for!

Considering that Einstein could easily have gotten about *five* Nobel Prizes, that's surprising. You have to go down the list, right? Special Relativity, General Relativity, his work on the existence of atoms from Brownian motion bouncing particles around… He had a *number* of insights that he *easily* could have gotten a Nobel Prize for.

The one for which Einstein *got* a Nobel Prize was the one about photons being particles. And Einstein was *hard-nosed* about this, if you read this quote here. "Light seems better modeled by assuming that its energy *is not …"* — now, *look* at that! — "… spread continuously over large volumes, but consists of a *finite number* of energy quanta that are *spatially localized*." They are in *one little tiny spot* — Einstein uses the word point "… and they move without dividing, and are absorbed and generated *only* as whole units."

People often say *Planck* is the one who came up with this. The truth is, Planck *dodged* this until *years* after Einstein brought it up! Planck did not want to go this route. Planck was very conservative. He was a brilliant man, but he had to be forced, *screaming* and *hollering,* to get to the point of coming up with the idea of Planck's constant. He *never* used the idea of photons as units. He didn't even use the photon quantization *equation* that we usually associate with him — that came later.

So, the real force for saying that photons are particles came from Einstein. And Feynman picked up on that! Feynman said, "Hey, I'm *good* with that! I'm gonna *follow that idea* and see where it goes!"



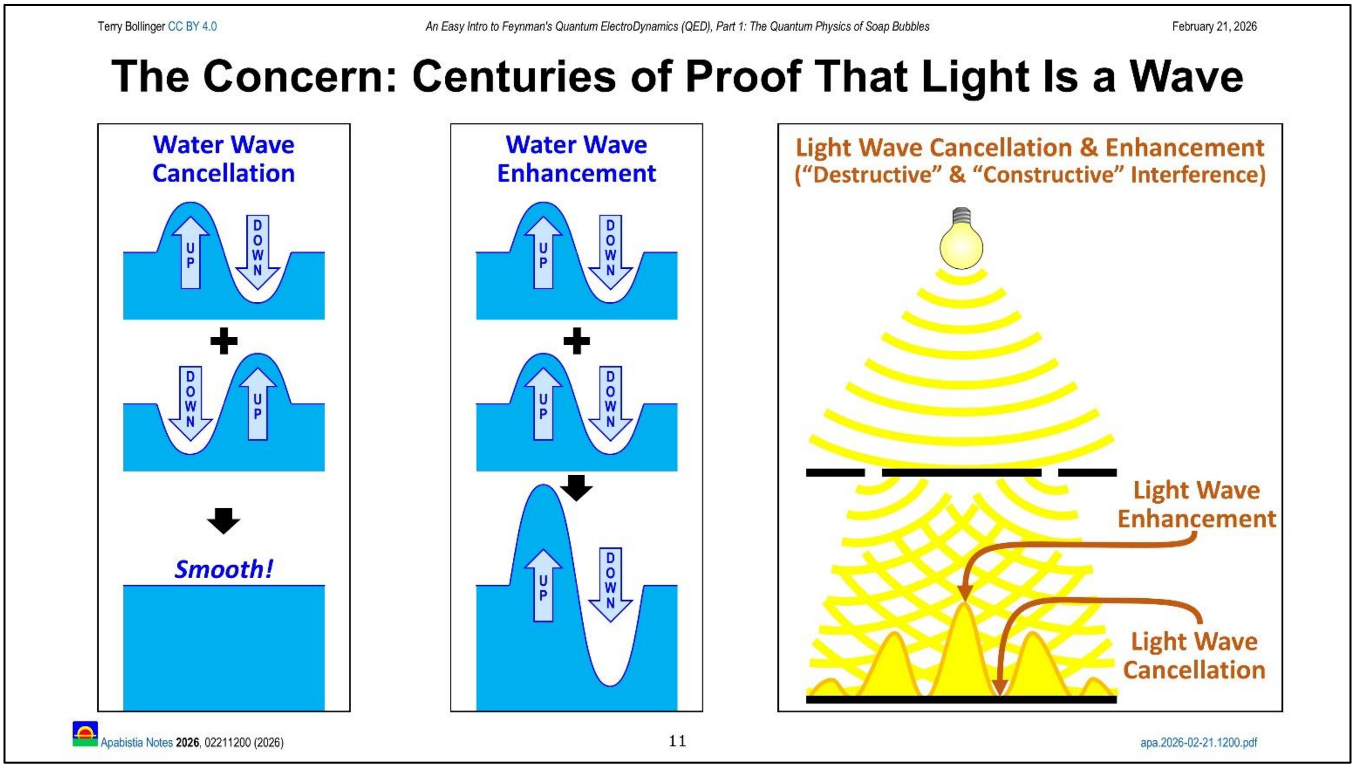

13:26 Einstein's photon idea *did not play well* (chuckle) at first! This is *characteristic* of the people who get Nobel Prizes. It does *not* mean that people *love* what they say when they come out with it!

So, when Einstein came up with his light-as-particles idea, people just looked at it and said, "That's *ridiculous*. That is *absolutely absurd*. We *know* that light is a wave. It *can't* be photons… and *you* are point-blank *saying,* 'It's a little particle traveling through space!'"

Even the Nobel *announcement* for Einstein's work refused to talk about photon quanta! Instead, they talked about "the photoelectric effect," which was kind of a weasel-wordy way of saying, "Yeah… he found something *very important* here… the *equations* all work. It's *extremely* predictive," — which is *important,* and is why he got the *Nobel Prize* for it! — So, extremely predictive, and the math works out right. "But, you know… the way Einstein *phrases* it… we're… *not* so sure about that," — because they just couldn't conceive that light quantization was a real thing.

And there are *good reasons* for that confusion! Because, *to this day*, wave-particle duality remains the *most baffling* feature of quantum mechanics. People can tell you they've "got it worked out," they've "got this," or that they've "got that," but… It is *baffling*! It is *still* baffling. It has *never ceased* to be baffling!

Einstein was *aware* of that. He *knew* that. But he said, "We've *got* to look at what's happening with this quantization, if we want to understand it."




14:58 Now, the emphasis here is that sometimes physics gets dressed up in *too complicated* a fashion. [So, here is an example of simplifying an idea to match everyday phenomena we know well.]

If you have ever *dug a hole*, you have noticed that, in the process of digging the hole, you also wind up with a *pile*. So you have a *pile*, and you have a *hole*.

If you can understand the ideas of *digging holes* and *making piles*, you understand the phenomenon called *interference*, because all interference is, is the mathematics of *digging holes* and *making piles*. You can dress it up in *all sorts* of fancy ways, but that's really *all* it adds up to.

If you look at the leftmost box here, *wave cancellation*, imagine two things: You have two waves heading toward each other. One of them is up-on-the-left and down-on-the-right, and the other one is down-on-the-left and up-on-the-right. What do you get?

They cancel each other out! This is just like filling in holes. The up-on-the-left side fills the hole on the left side, and vice versa. And you wind up with a smooth surface.

That's called *destructive interference*. It means the waves *cancel each other out*.

Now, the other thing that can happen is you've got two piles that *pile up on top of each other*. So you wind up *digging the hole deeper* and *making the pile higher*.

[That's called *constructive interference*. It means the waves *add to each other*.]

The *same thing* happens with light. In fact, with *any* kind of wave phenomenon. It's the same idea, just more *dynamic*.

With your dirt piles kind of staying there for a while, it's easier to visualize the situation when you're doing piles and holes. But it's the same idea with light and other waves; it's just that working the piles goes a lot faster, and they change a lot more quickly. But it's still the same idea.

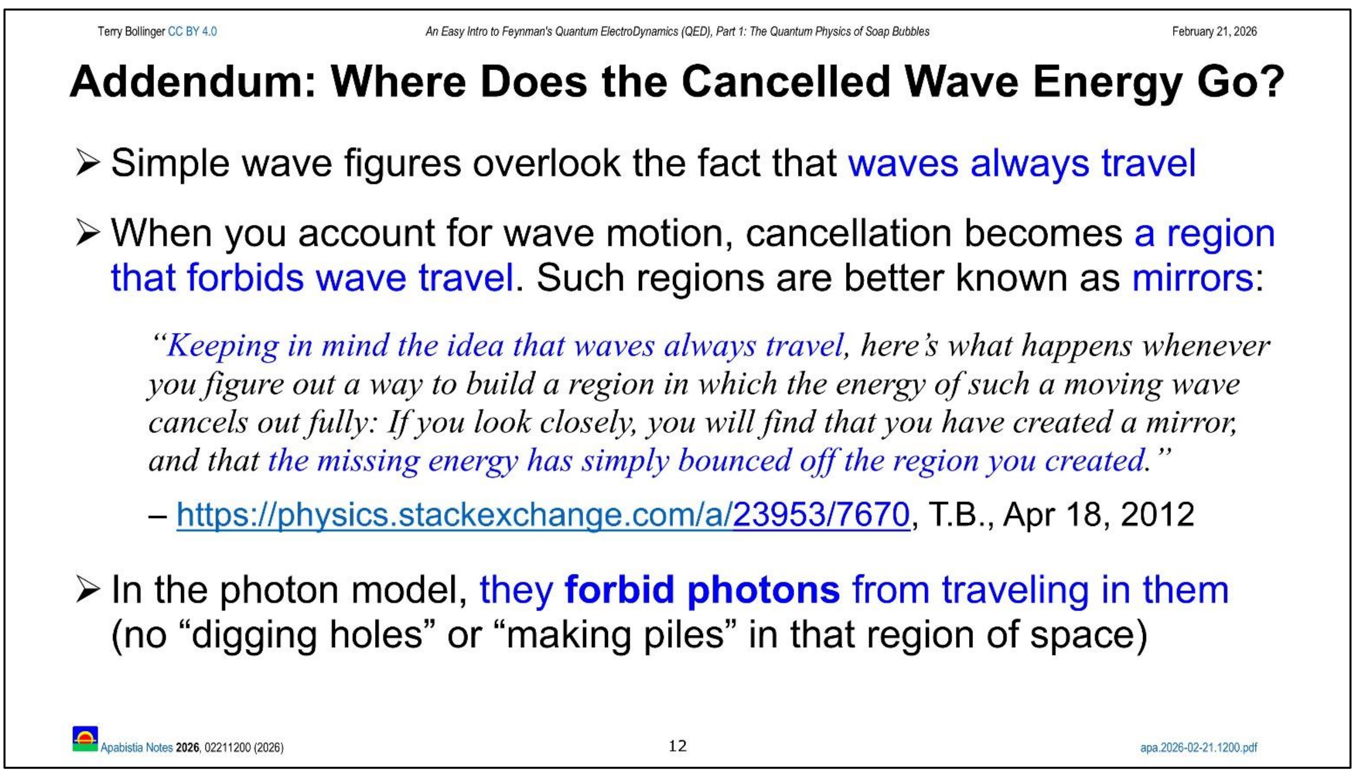
So, when you shine a light through two slits… (I'm simplifying some details here; this would be a monochromatic source here; I want to be particular about the frequency I use.) But if you take a source of light, and you run it through two slits, you get interference. Everybody's heard of that one, right? The two-slit experiment! Well, it works with photons. But for *photons*, it's been known for *centuries*.

So people knew that if you do this — if you put light through two holes — you wind up with this *marvelous* little *pattern* on the far side!

(And by the way, this experiment is a *lot harder* to do than you might think. There are some good YouTube videos on how to do it, but it is trickier to do. But it also has been *done*, and has been *known*, for a very long time.)

This is one of the reasons why people said, "What *is* this? What is this *particle* stuff? *What?* What are you *talking about*, Einstein? What's *wrong* with you?"

They eventually came around, but agreement was *not* the reaction they gave him at first!




17:29 This is something I'm just going to mention in passing, because it *does* make a difference.

When you look at that, and you say, "Well, two waves cancel out, and you get nothing." But if you know anything about energy conservation, your brain should be saying, "*Wait a minute, wait a minute*… That doesn't *sound right*, because you can't cancel out to *nothing!"* If you add them together constructively, you can say, "Oh, yeah, I just added the energy." But waves always have energy, so what happened to the energy in the *cancellation* case?

And that's actually a *very good question*. It's one that you need to look at *carefully*.

When I re-encountered this while preparing these slides, I went on the internet, and I looked for something about that. I found this quote by some guy named *Terry Bollinger*… I *literally* had forgotten my own quote on this! So, this was just something in the Stack Exchange, but the point is (chuckle), I'd forgotten my own point!

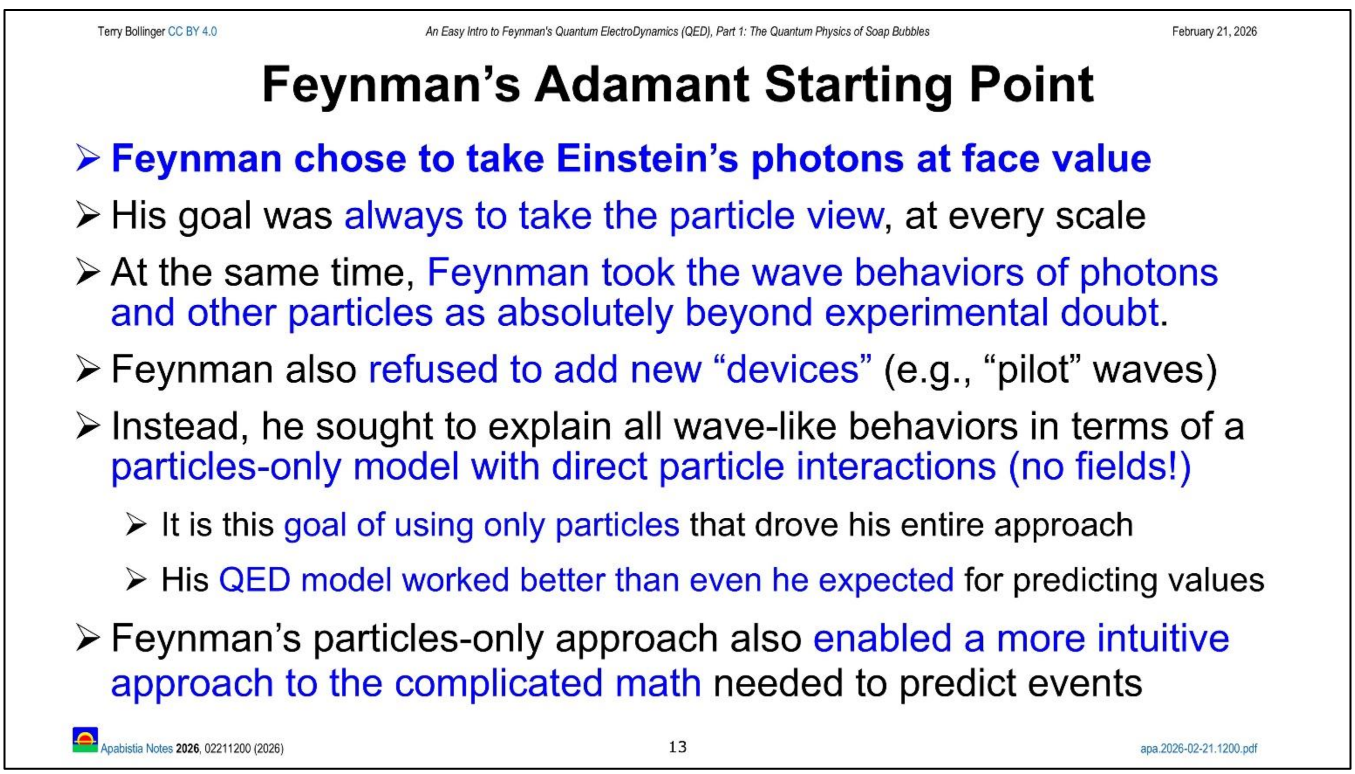
The point is very simple: When you make a cancellation area in optics, what you've *really* done is *create a mirror*.

You're making a region in which you *can't "dig holes" anymore*! So, you've got your little hole diggers coming along there and saying, "*I want to dig holes here!*" And there's this fence that says, "You may *not* dig holes in this area! We are a *forbidden area*! We do not allow *hole-digging* or *pile-pushing*! You *must* go somewhere else!"

And you go, "*Alright*…" So the hole-digger bounces off and goes in another direction.

That's pretty much what happens with *all sorts* of phenomena. If you look at a peacock feather, with those *beautiful* colors in the peacock feather, that's *exactly* what's happening. The peacock feathers create a *little region* where, essentially, there is a *sign* in front that says, "*No holes allowed for this frequency of light!*" So the blue light just bounces right off, or the red light, or whichever frequency it is that they have forbidden.

So, it's an interesting way to think about this cancellation. It's the idea that any phenomenon that looks like a mirror has some variation of this cancellation effect. It's *forbidding* the entry of photons into that area.




19:32 Feynman's starting point was exactly Einstein's viewpoint. He took Einstein's viewpoint and said, "I'm going to take it at *face value*! I'm gonna look at *particles only*, and *see if it works!*"

To the best of my knowledge, *no one* had done this before. And the fact that Feynman *did* this, and at the same time *fully acknowledged* all of the *wave behaviors* of light, was unique.

There is an easy thing to do in research, which is this: You look at an idea, and you say, "This is *important*. Photons are *particles*."

So far, so good. The trouble, then, is if you then go on to the next step (chuckle), and start saying things like this:

"So… *everything* where it *doesn't* look like a particle… *must be bad experimentation!*"

And *as soon* as you go down that path, you're in *trouble!* Science doesn't work that way! You've got to look at the *full* set of experiments and ask, "What does it *all* say?"

Feynman was good at two analytical things: First, he took an adamant viewpoint and said:

"These things are particles!"

But he also said:

"… and *every single blooming non-particle behavior* that we see is *exactly* what we see."

So, when you see the *interference*, it's the *interference*. There's *never* been any deviation from that one at any scale, since when you take an individual photon, *it still does it*.

So Feynman said, "Take them *both* seriously!" This is what Feynman did that no one had done before. He took this idea of saying that, "Well, they are *particles*, as Einstein said. But *something* strange is going on here to produce these wave behaviors."

Feynman also refused to add "devices." An example of adding devices is if you look at something called the pilot wave theory. This is the idea that de Broglie originally came up with; he broke photon behavior up into two parts.

Most of the *Copenhagen* version of quantum mechanics *also* breaks photon behavior up into two parts. You've either got a *wave*, or you've got a *particle*.

And then in both models, you have some *mix* of the two devices. They either *alternate* or, in the case of pilot waves, they actually exist *at the same time*.

Feynman refused to do that. He said, "No… *no*. It's got to be *one or the other*." And he chose the particles.

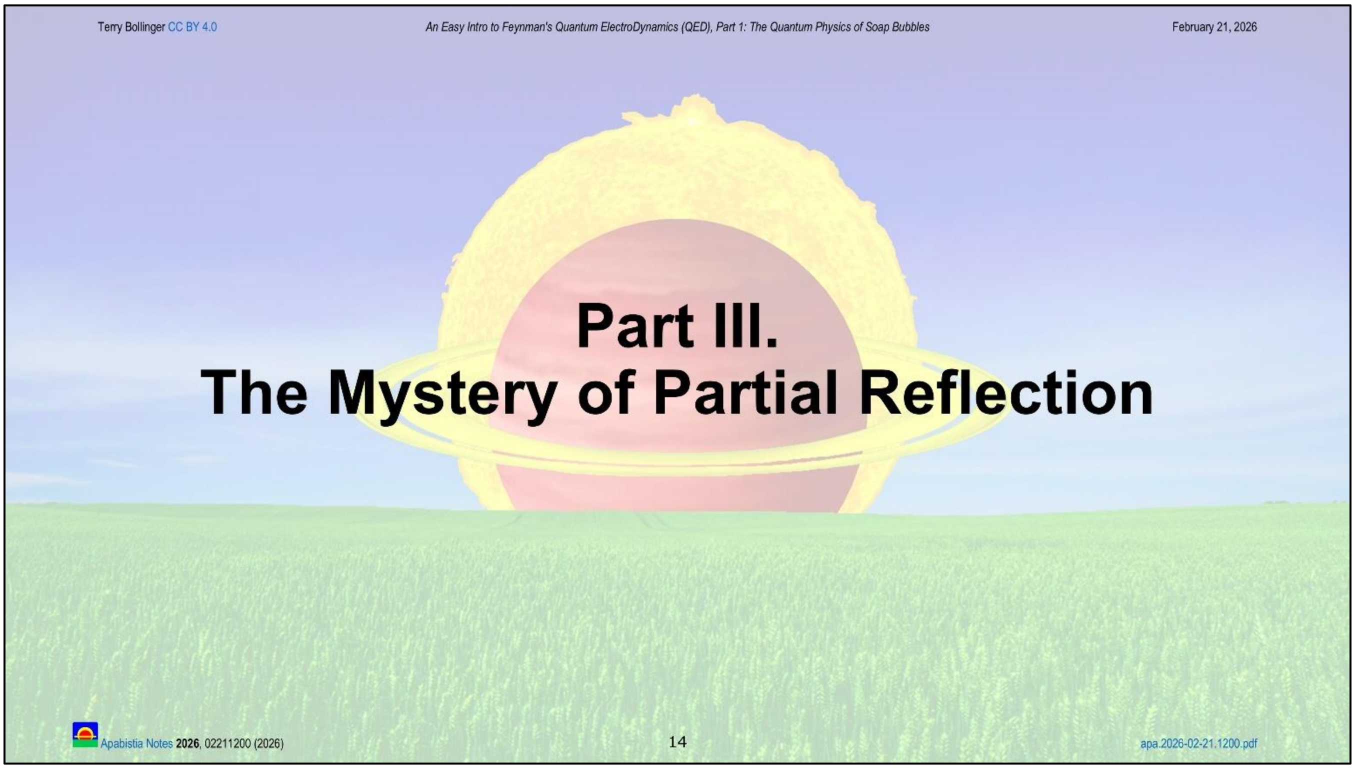
So, in doing so, he *avoided* the concept of fields. And this got one of his co-winners of the Nobel Prize a little miffed at him (chuckle), because *not everybody agreed* with the idea that there were no fields! So Feynman took an interesting perspective on that.

What *happened* when he did that — when he simplified as *much as he could*, and said, "Particles, particles, particles!" (Eventually, he dropped even the *atoms* which he had used in his Ph.D. thesis, and just said, "Electrons, photons; forget about everything else!") — is he wound up getting *better math*.

The math that he wound up with could predict things that *nobody else could predict*. And that's *because* of the simplicity. This is not a coincidence here. He went from *maximum simplicity*, but taking *everything* into account, and said, "What model takes *all of that simplicity*, and then *builds* it into something new?" And this is what he did.

So he came up with this QED model that turned out, *to his own surprise*, to be extremely predictive. There are recorded statements of him saying, like, "I didn't think that would *work!*" So Feynman was just like, you know (chuckle), "I *thought* it was a *good idea*, but I didn't really think it would work *that* well!"

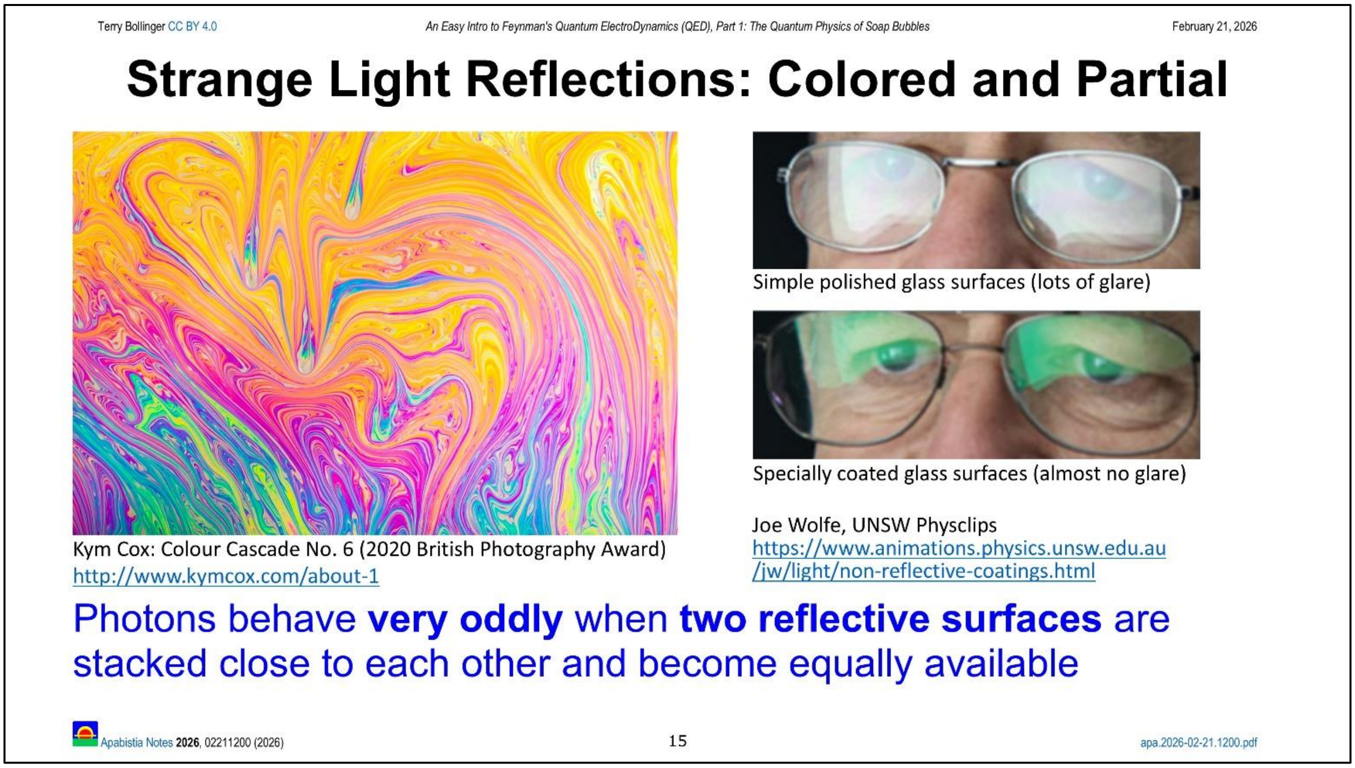
But it *did!* And it started predicting things that then the experimentation started verifying out to 6, 7, 8, 9 decimal places. So, he was on to something, and it took a little while for that to be fully realized.




22:55 So, what was Feynman looking at?

What was the logic behind how he explained a particle that, at the same time, does all the optical things that you see?

And one of the paths for doing that — which, apparently, is one of the paths that inspired him in some of this — is the mystery of *partial reflection*.




23:17 What is partial reflection?

If you have no-glare glasses, you know this. If you have an old pair of glasses, they just glare terribly. And then, you've got these newfangled glasses — that's how *old* I am: "The newfangled glasses," quote-unquote, because I'm back from the era when my *original* pairs of glasses didn't do this!

With the new ones, you can see the person's eyes better, and the person inside sees a lot less glare from the outside world. That's a *marvelous* little technology!

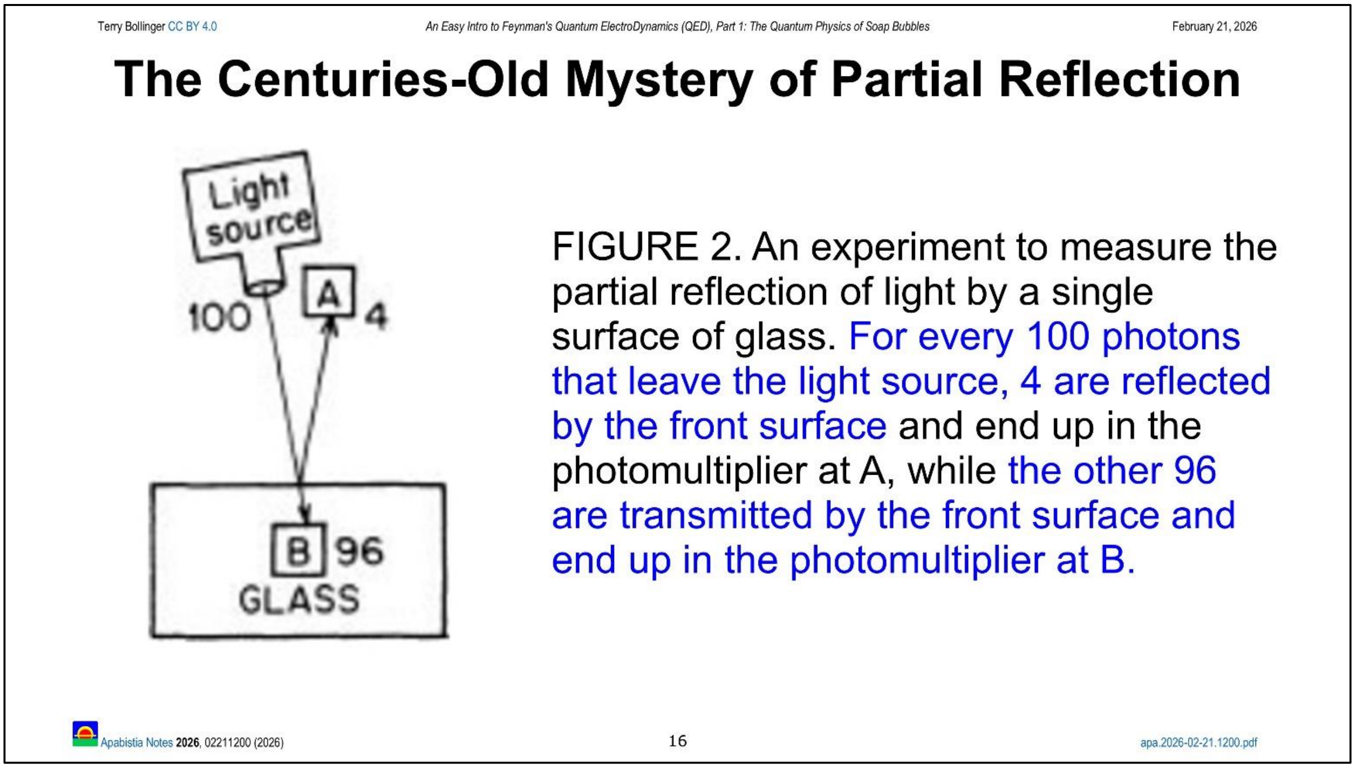
And, doing that requires a deeper understanding of light. It turns out the same phenomenon is very closely connected to the effect that causes *shimmering colors* when you have a little bit of oil on top of water. It causes very similar, very similar shimmering colors from soap bubbles. It's essentially the same effect, just in a slightly different form.

So, you have these examples of what's called *partial reflection*. And you also have versions where you have different colors popping up. In most of your no-glare sunglasses, you can see a little bit of green. In this example, this guy's got a little bit of green in his no-glare glasses.

So, what is the *key characteristic* that causes this to happen, and why is it important?

I love this, because that seems like such a simple question! Okay, then: What makes these things happen, and what's the *key thing* you have to have to do to make those things happen?

It turns out to be nothing more than *two reflective surfaces close to each other!* That's pretty simple! There's not a whole lot to that! But what's going *on* with this?




25:00 This effect has been known since at least Newton's time and longer: That glass has these odd characteristics in how it reflects light. And the characteristics have to do with how *thick* the glass is.

So, if you have glass of a certain thickness, and you send some photons at it, you get what's called *partial reflection*: You get photons that come back, in small numbers in most cases, and you have photons that just go through.

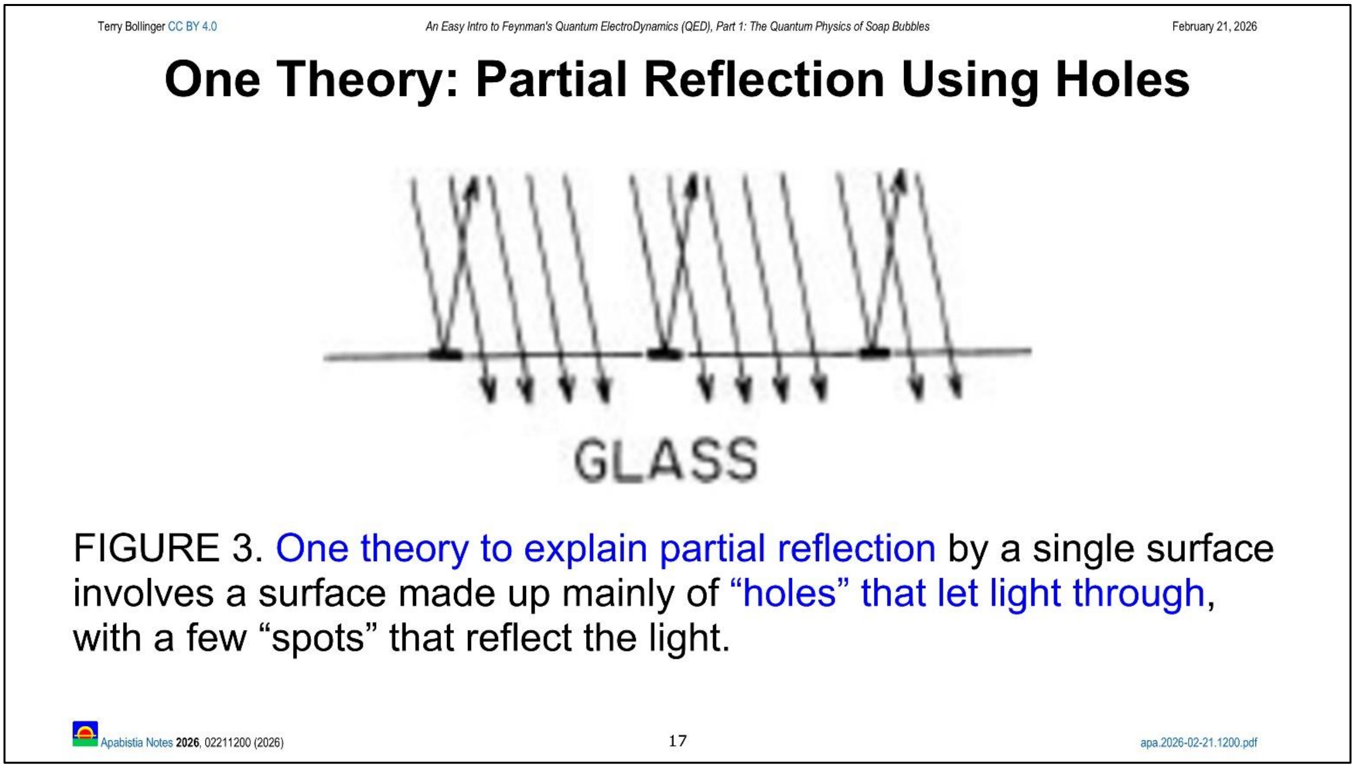


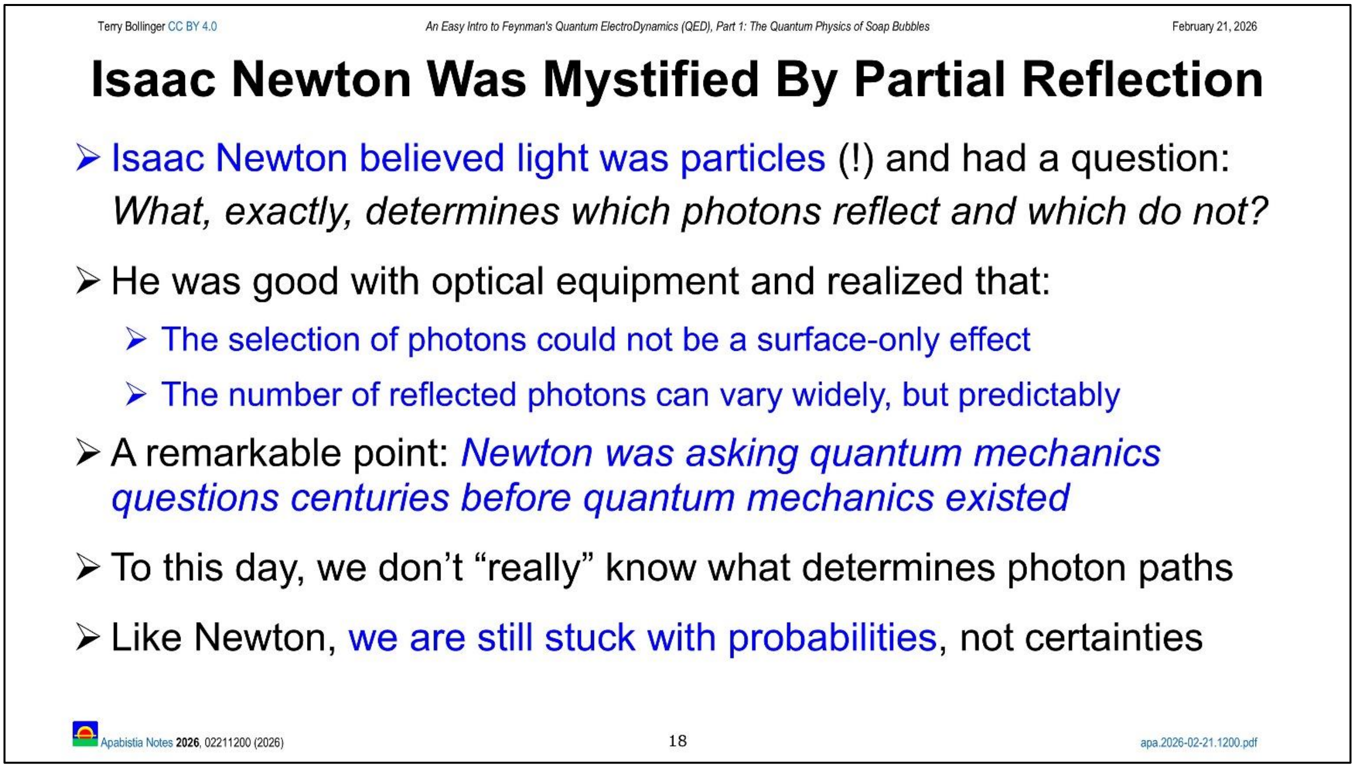

FIGURE 3. One theory to explain partial reflection by a single surface involves a surface made up mainly of "holes" that let light through, with a few "spots" that reflect the light.

25:34 At the time of Newton, it was fascinating because Isaac Newton *tried* to understand this phenomenon. He *knew* that something strange was going on with this. He was going, like, "This… *this* is *definitely* weird." And he *loved* optics, so he was trying to find out, as much as he could, about how this phenomenon worked.

He discountenanced — he discarded — one theory, which was that there are little *holes* in light-reflecting surfaces, so that most of the light goes through the holes. There are occasional little *spots,* where those spots *reflect* light, and *that's* where you get the partial reflection.

If you go through the full argument — and Feynman covers this in his book nicely — Newton was able to eliminate that model by saying, "*No*. Because I can *polish* class — because I can make it arbitrarily smooth — I can *get rid* of whatever these little reflecting areas are. So it *can't* be that simple." And there are other reasons why Newton realized it can't be that simple.

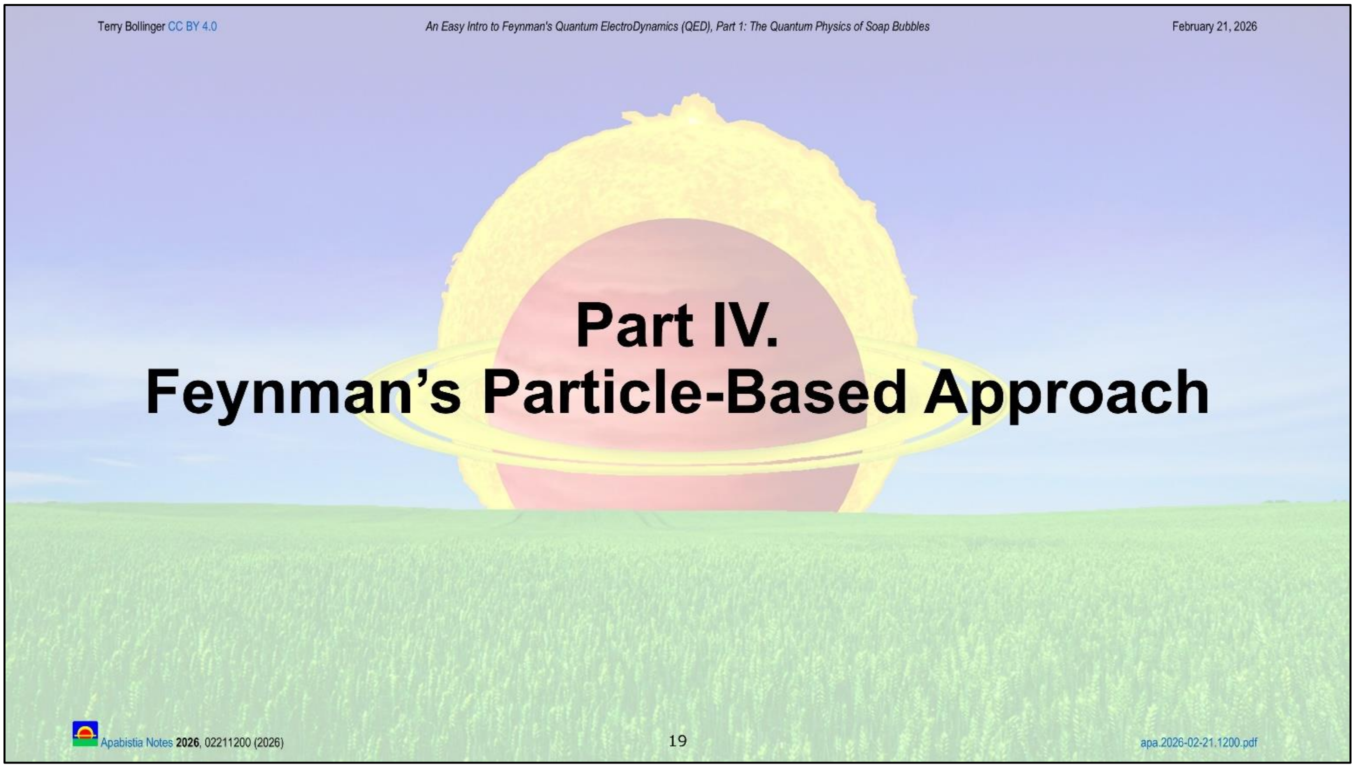
So what *are* the characteristics? What makes glass reflect sometimes, and sometimes not, and what are the experimental numbers that affect partial reflection?



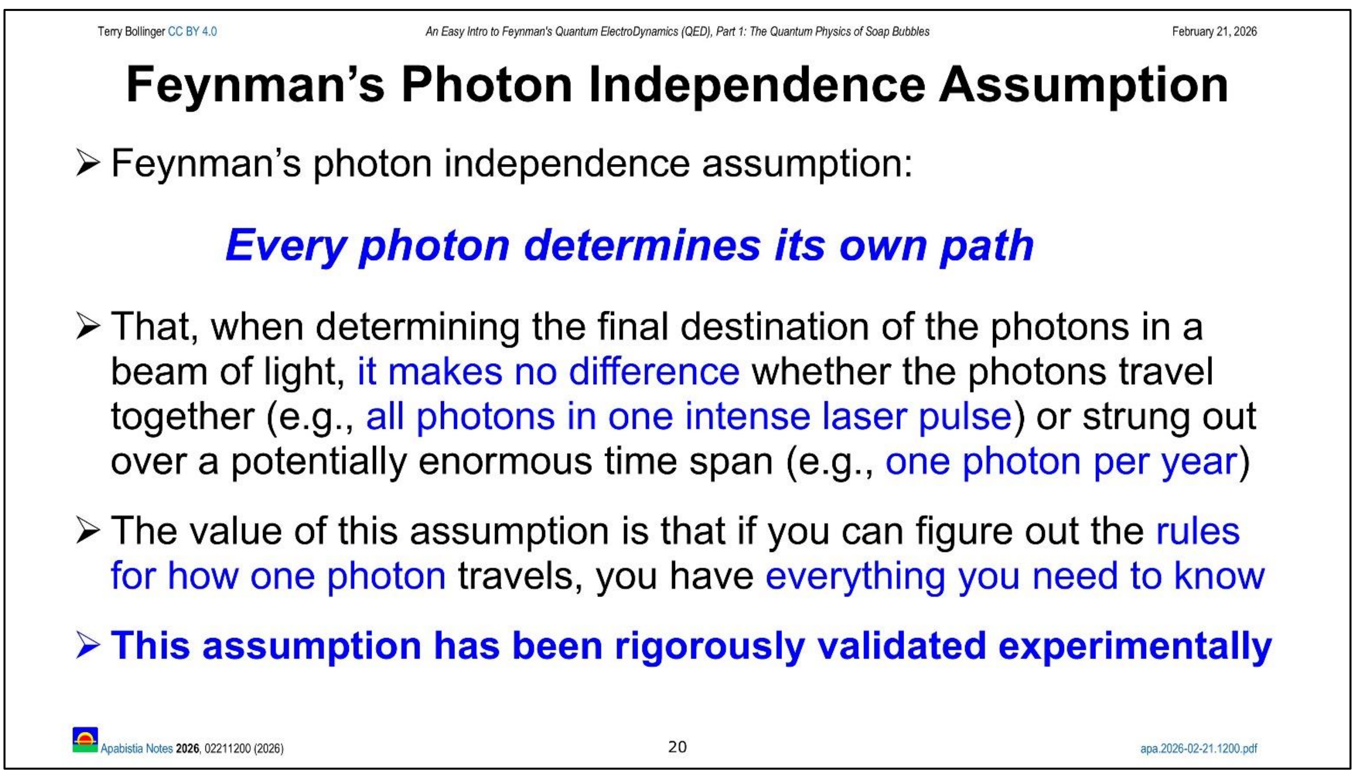

26:38 Photon selection in reflection could *not* be a surface-only effect, was what Newton realized. And it came up later, as he looked deeper, that there had to be some connection with the *actual structure of the glass itself*.

And for Newton to be asking these questions is fascinating. And again, even now, we have our little mysteries, and sometimes we just don't have the *mechanisms* to answer them. Newton was asking questions about quantum mechanics *centuries* before quantum mechanics existed! He was saying, "I *know* that this is not just a simple surface phenomenon. I *know* that there's something very interesting going on. I can characterize *some* of the features of that…"

But he couldn't come up with any *broad mechanism* — he was unable to come up with an *explanation*. And even to this day, just as *Newton* was stuck on that point, we're *still* stuck, in a way, because we *still* do probabilities, not certainties. It's one of the classic complaints about quantum mechanics, that when you go down to this level, you wind up with *probabilities*, but you just *never* get these *absolutes* that you have in classical physics.




27:47 Feynman's particle-based approach.




27:49 Feynman's particle-based approach — again, taken from Einstein.

Here's an important initial qualifier: When we go at a problem like this — and when Feynman went at a problem like this — you need to know your own assumptions. And you need to know them *very well*, because it's *so easy* to sort of "gloss over" something, and only later realize you were actually thinking something a little bit different.

Feynman's independence assumption was this: *Every photon determines its own path.* Why would he say that? Why would he think that? The reason he would think that is because *experimentation backs it up*.

Feynman was adamant, adamant, *adamant* about following experimentation: "What does the experiment show you?"

And what experimentation shows you is that, if you dim a light that's going to a surface that has this effect of partial reflection, and if you do the experiment, and instead of putting a *gazillion* photons all at once in a laser pulse, or a weak wave where it's still just a wave, "What if you just keep thinning it down until finally you're just getting, like, one particle, one photon, for some *ridiculously* long period of time, maybe even a year?"

No reason why not! One photon per year, *twink!*, goes to the little reflecting surface, bounces back up, and you record the results. Did the photon bounce? Did the photon go through? Did the photon follow a certain path?

Here's what experimentation says. *It doesn't matter.* One photon? One trillion photons? Some unbelievable number of photons? *They all follow the same rules!* This *single* photon has the ability to figure out that path, and figure out the probabilities, *on its own,* as some enormous mass of photons.

What does that mean? It means that if you talk about interference, you *don't* have to think about a whole bunch of photons interfering with each other. You have to focus *on that one photon*. You have to figure out what that one photon is doing, and *how* it is doing it. And that leads you down a *very* interesting path.

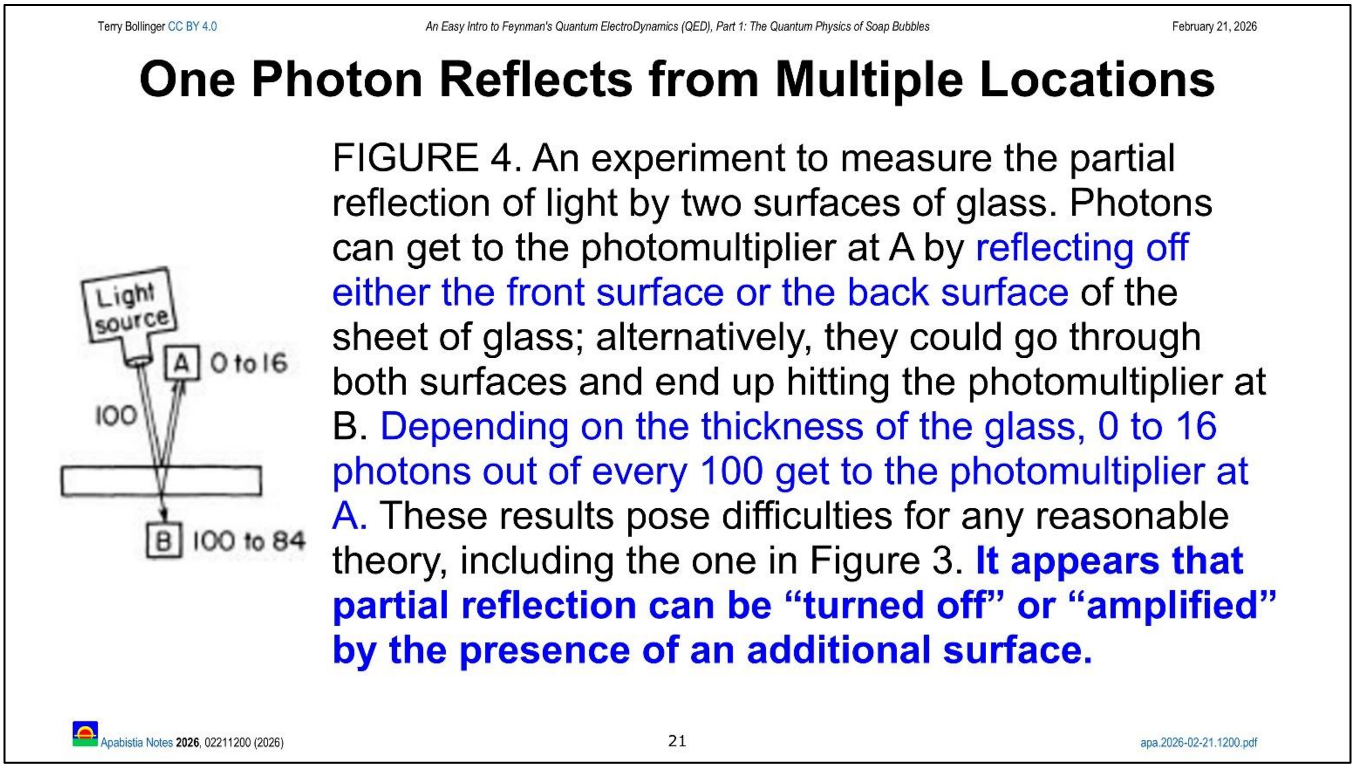
So, this assumption is something that's very well validated experimentally. But it's easy to *not recognize it*, because it's just *so counterintuitive!*

I'll give a more extreme example. We have Einstein lenses that are millions of light-years across. And, according to this principle, *one* photon from the other side of the universe, literally, can go through that lens, through that gravitational lens, through the *entire* lens, and come over on this side to give a *single focus point* on a telescope here at Earth. And it's all *exactly the same* as if it had been an *intense pulse* that was bright enough to see across the entire galaxy!

So… *think* about that! How does *one photon* know the *same math*, exactly, as some *enormous* burst that would illuminate the *entire* set of galaxies?

So that's how strange this gets! But experimentally, including with lenses like that, that's what we *always* see: Individual photons *have the whole story*. If you can understand the photon, you can understand the underlying physics.

That's *remarkable*. That's why Feynman was able to simplify things.

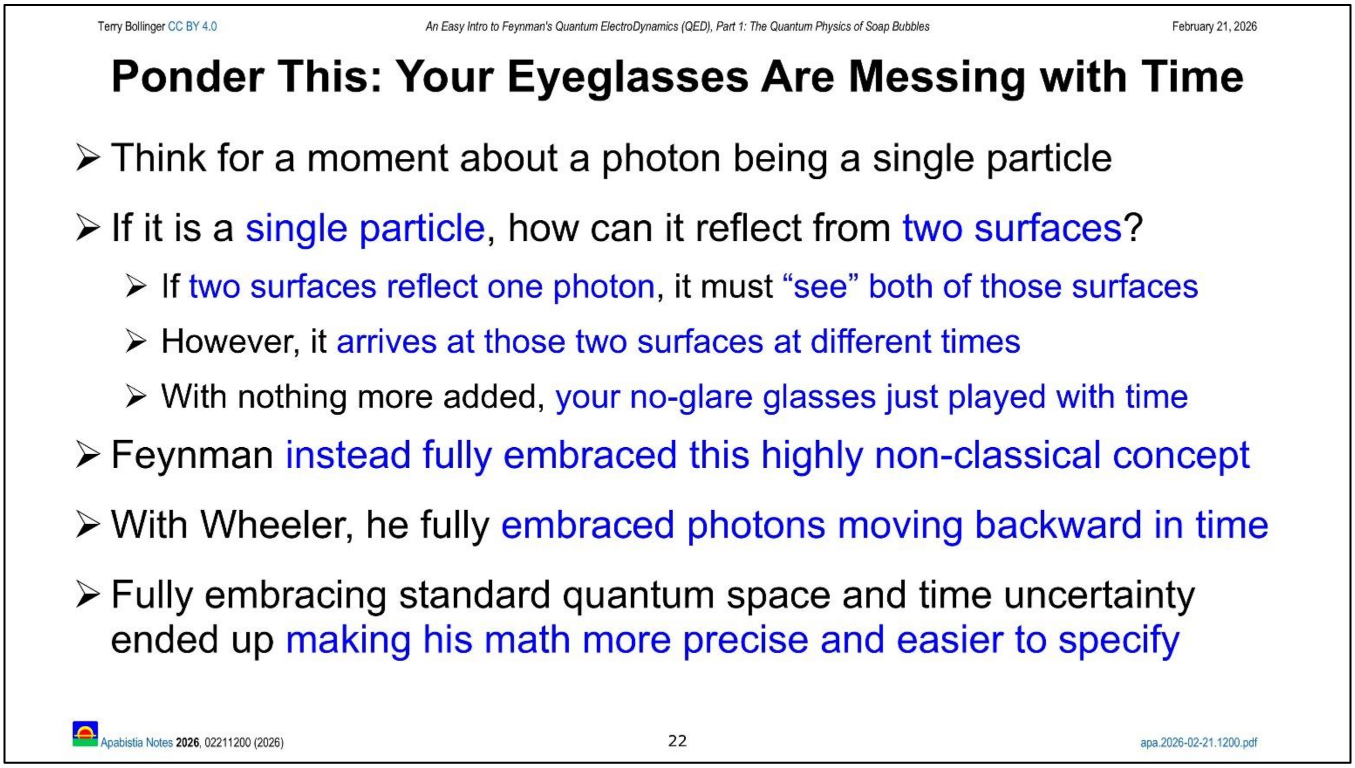



31:18 One photon multiplies… reflects from multiple locations. That's what I was saying about these surfaces. So you have two surfaces.

This is the key insight. If you want to understand these partial reflections, if you want to understand these colors, you have to recognize that the photon is bouncing off of *two* layers of a light-reflecting surface.

So the partial reflection is amplified, or turned off, one or the other, by the presence of the additional surface.

Now, if light is a particle, can you see there's a problem here? There's a *problem* here! There's a *really interesting* problem here!




31:53 Your eyeglasses — if you have eyeglasses that have anti-glare on them — those anti-glare coatings are *messing with time*.

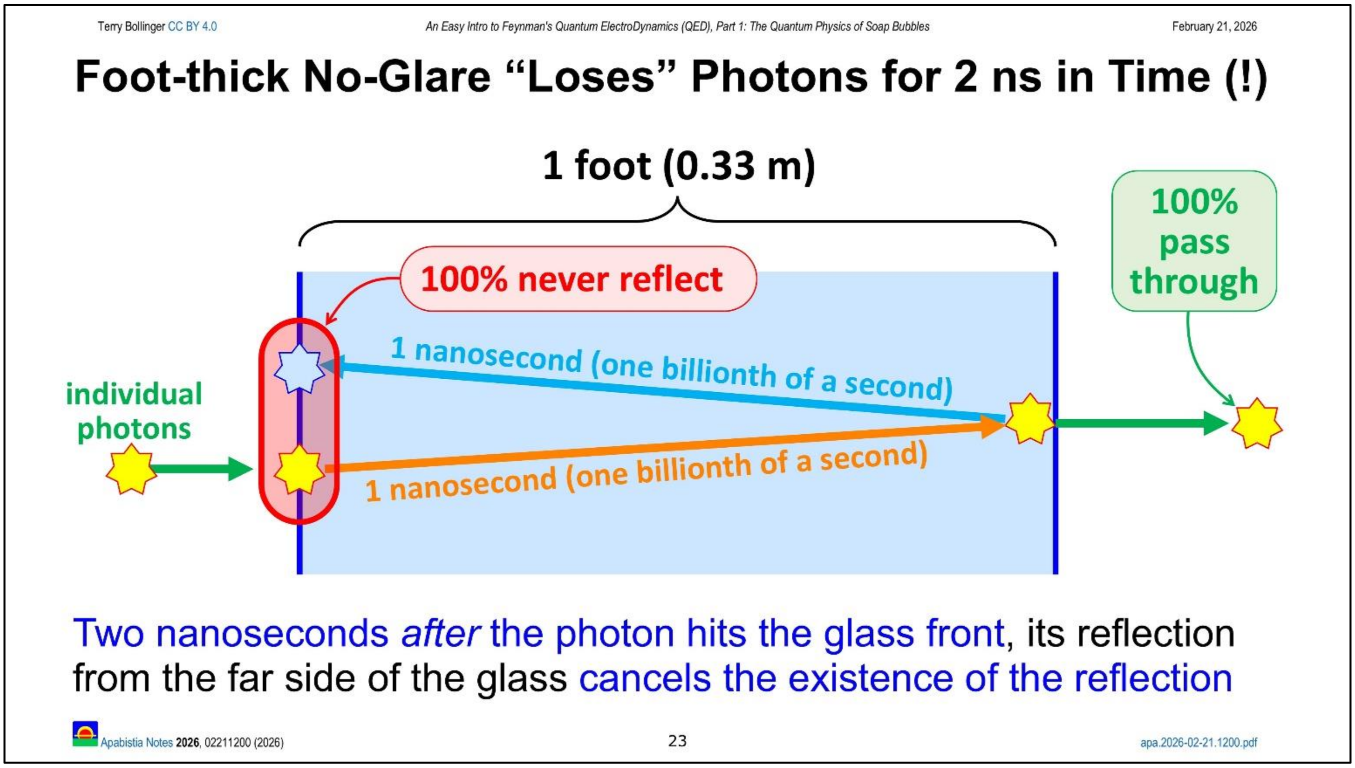
And I don't mean that in a *figurative* sense. I mean, in a quite literal sense, that *without ambiguity of time*, your "anti-glare" would not be "anti-glare." It would *not* be able to stop the photons from creating that glare. The photon, if it's a particle, has to see *both* of those surfaces!

And this is where Feynman *refused* to back off. He said, "I'm *still* going to stick with particles. But I'm going to look at the particles in terms of saying, 'They can do things that *bend* our usual definitions of *how* particles travel.'"

He's saying that, "In *some sense*, in *some way*, *this* is how you calculate it." And he intentionally said, "I don't *know* how this works; you've got to follow the algorithms." He's not trying to *explain* it; he's saying, "This is how you *calculate* it."

And the calculation is that you show the photon going to *both* surfaces.

So this is a *non-classical* concept. You can't *do this* with a baseball. You can't have a baseball bounce off *two surfaces,* and then come back and interact with itself!




33:04 This is *so strange* that I want to point this out with an extended example.

If you have a no-glare layer on your glasses, most such no-glare layers are obviously extremely thin. But you can make them *thick*. You have to be much more precise when you do this, by the way. This is not an *easy* thing to do, but it absolutely *is* doable, and it's been done *many times*. You can, for example, have a length such as an entire foot, which, conveniently, is almost exactly 1 nanosecond of light travel time. (It will actually be a little slower on the glass.)

But, you can have that *one foot*, and you can have the *same* interference effect, so that photons are guaranteed *not* to glare — that they'll go through the *entire thing* with 100% certainty. But the *only* way you can calculate that is to *assume* that the photon is *lost in time* for about 2 nanoseconds.

What do I mean by "lost in time?"

You *can't* have the non-reflection effect until those 2 nanoseconds are up!

If you try to *look* at things at one nanosecond, or at a *fraction* of a nanosecond, or at some other *earlier* time, photons are hard to detect that way, but you can have something like an electron doing the same thing, *which you can* — if you say, "No, I'm gonna *cheat!* I'm gonna *look early* and ask, 'Where's the particle at?'" — You'll find out the effect *disappears!*

So, you have to let the *entire 2 nanoseconds* go by before you get the interference effect.

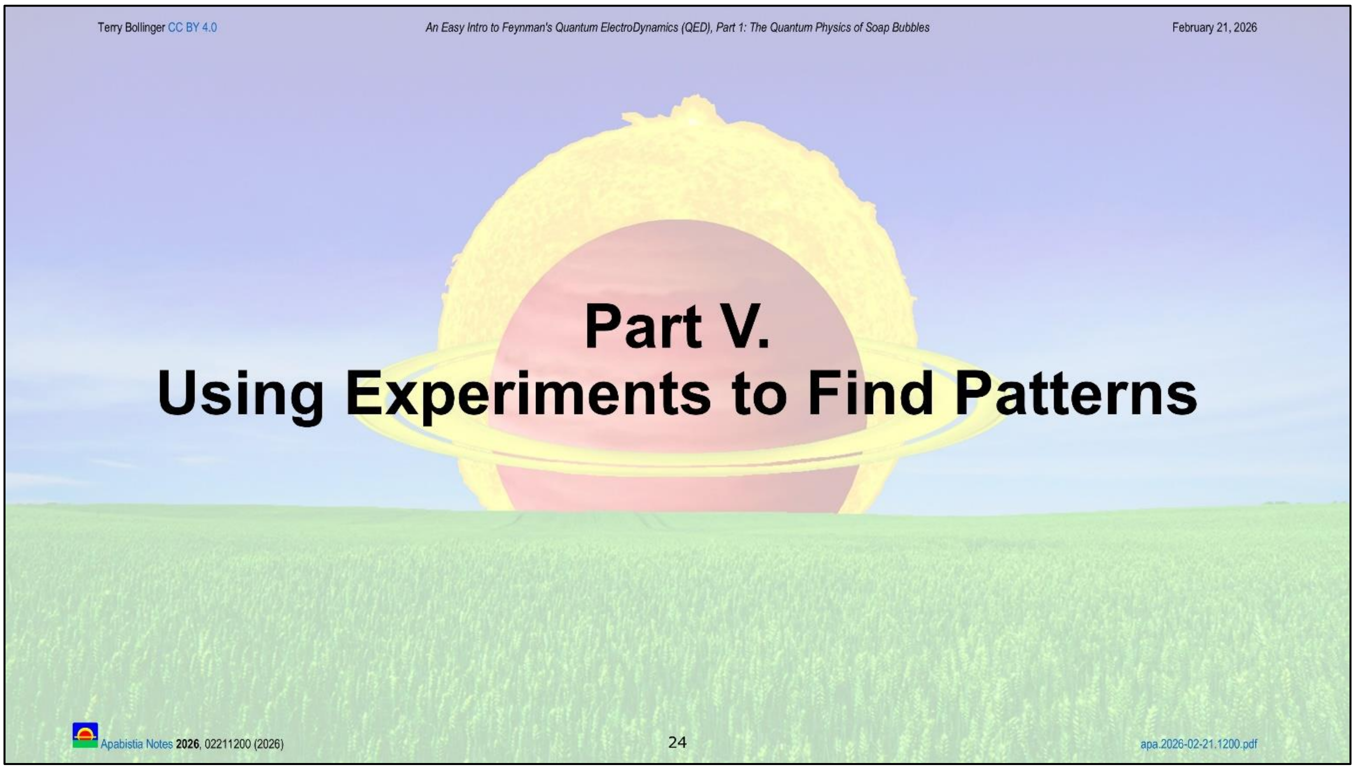
This is *not* your usual concept in classical physics of how particles work! And the beauty of the Feynman diagrams is that he said, "I'm going to *assume* it's a particle… but I'm also going to allow that particle to do *different pathways* — to try *different things* — and then *add them all together*.

So it was a *marvelous* insight he had. But it required *bending* our usual definitions of time.

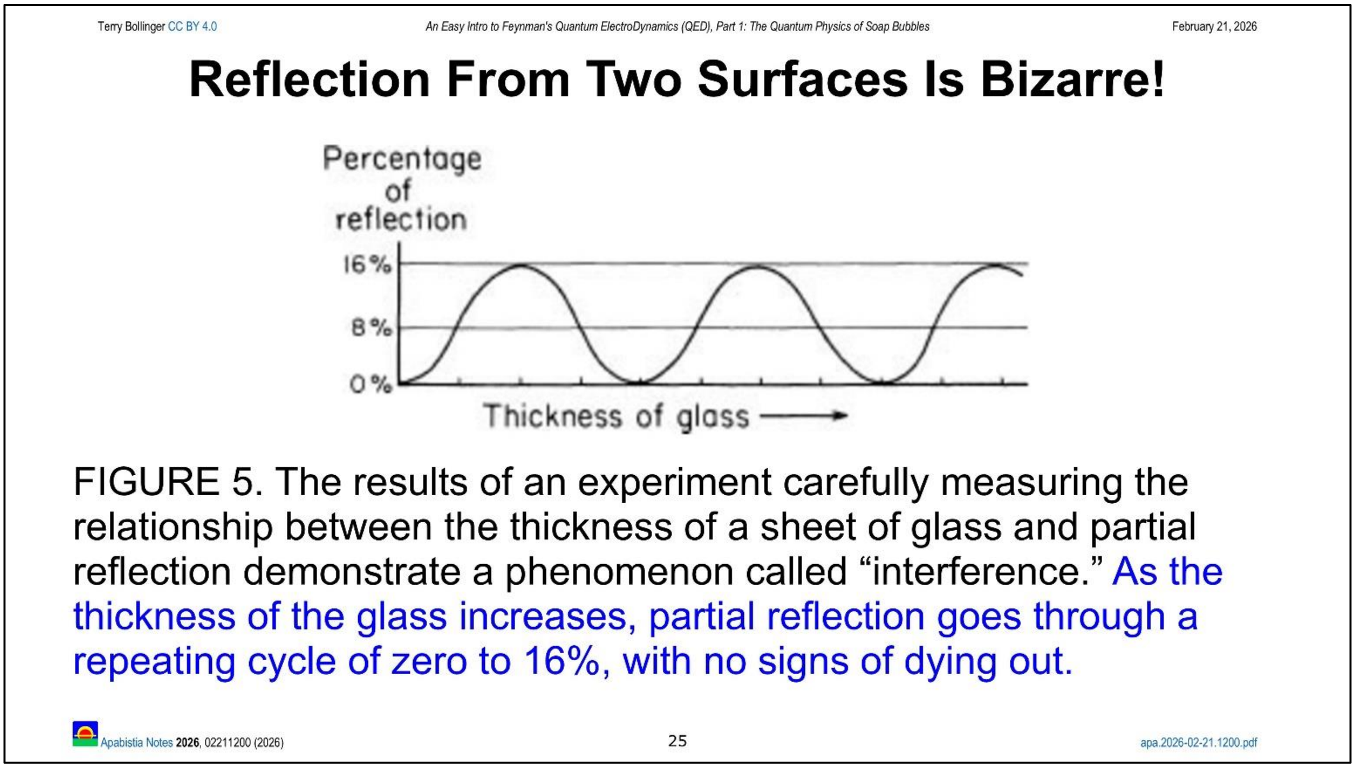
I am amused, sometimes, when I see articles that talk about "New quantum results have shown… *ambiguity across time!*" It *amuses* me because that's *always* been there — and this is a good example *right here!*

Just to do anti-glare *requires* an ambiguity in time for the quantum mechanics to *work*. This is similar to the spatial ambiguity; it's just working in the time domain.

*It's everywhere!* It's *not* rare! You *don't* have to have a whole new experiment to get ambiguity in time, because *all* of these self-interfering experiments do it. Anytime you use the word "self-interference," you're playing with time, space, or both. The very fact that a particle is "interfering with itself" means it's *seeing different versions* of itself, at different locations, and at different times.




35:43 Using experiments to find patterns! We've got this *interference effect*. It's *really interesting*. What does it say about *reality*? Can you find something *deeper* about that?




35:55 If you *map this out* — and this is the importance of *experimentation!* — You say, "Well, okay… if I can't figure out *how* this works, and it doesn't make any *sense*, classically, can I at least *characterize* what the critical circumstances are?"

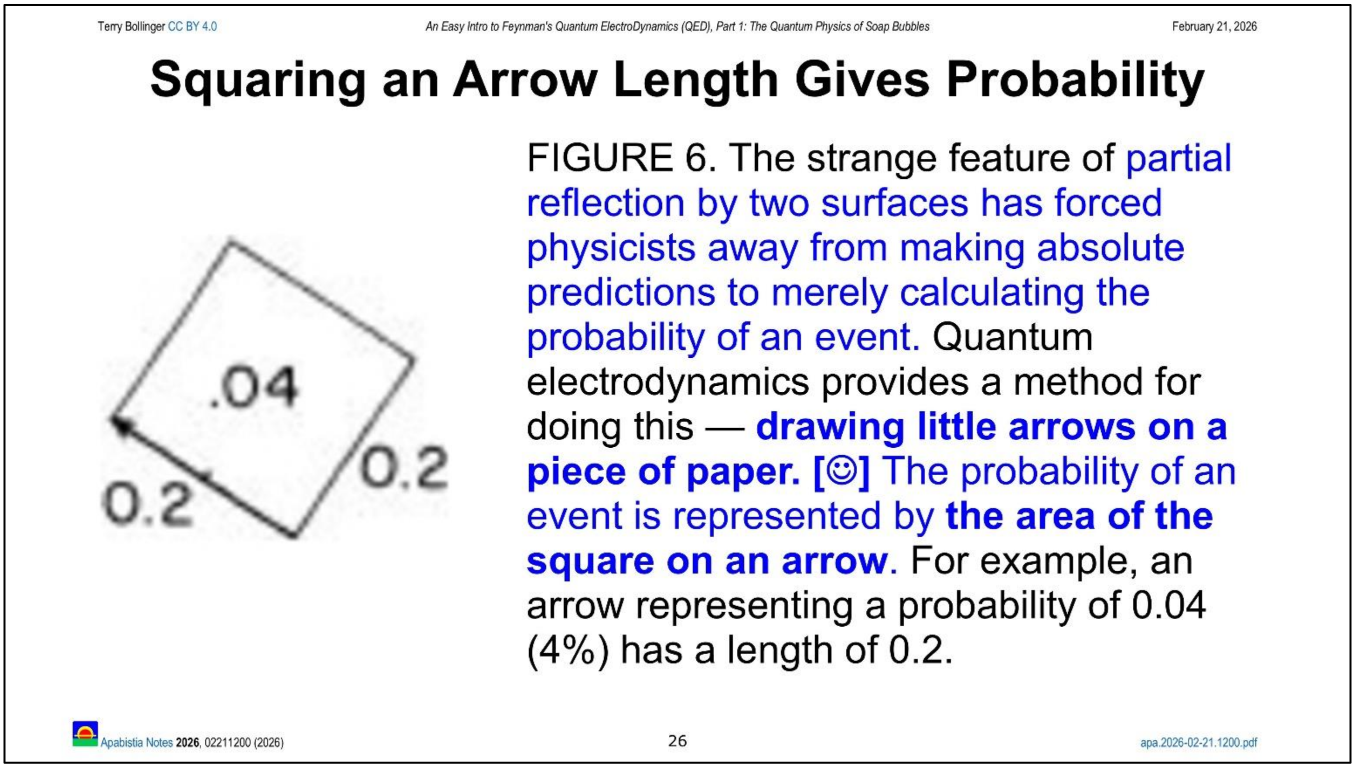
And *yes*, you *can*! And what you find out is probably even *stranger!*

It's that as you *increase* the thickness of the glass, you start *changing* the amount of reflection. It goes up to a *maximum*, in this case of about 16%. And it goes down to a *minimum* of zero, the no-glare case. That's the one that they shoot for with your eyeglasses, although it's more complicated because you have many frequencies there.

So, yeah… You go, like: "*How? What?* (chuckle) *How* does *this* work?"

And by the way, Newton was *aware* of this stuff, and he was like, "I don't know!" He couldn't explain it! But that didn't keep him from *noting* it and saying, "This is *extremely* interesting, what's going on here."

So what *is* going on? So, Feynman used this kind of data to say, "Okay, I'm going to *stick to the particle model* — stick, stick, *stick* to the particle model, to Einstein's particle model — and *see what I can do.*




37:12 And what he *found* was that there's a *little arrow* associated with this. You have to *re-represent* the probability as an *arrow*. And actually, as it turns out, the length of that arrow is the *square root* of whatever that probability is.

So, if you have a .04 — a 4% probability of the photon reflecting — Feynman said, "How do I *take care* of this? I'm gonna… *draw a little arrow!*"

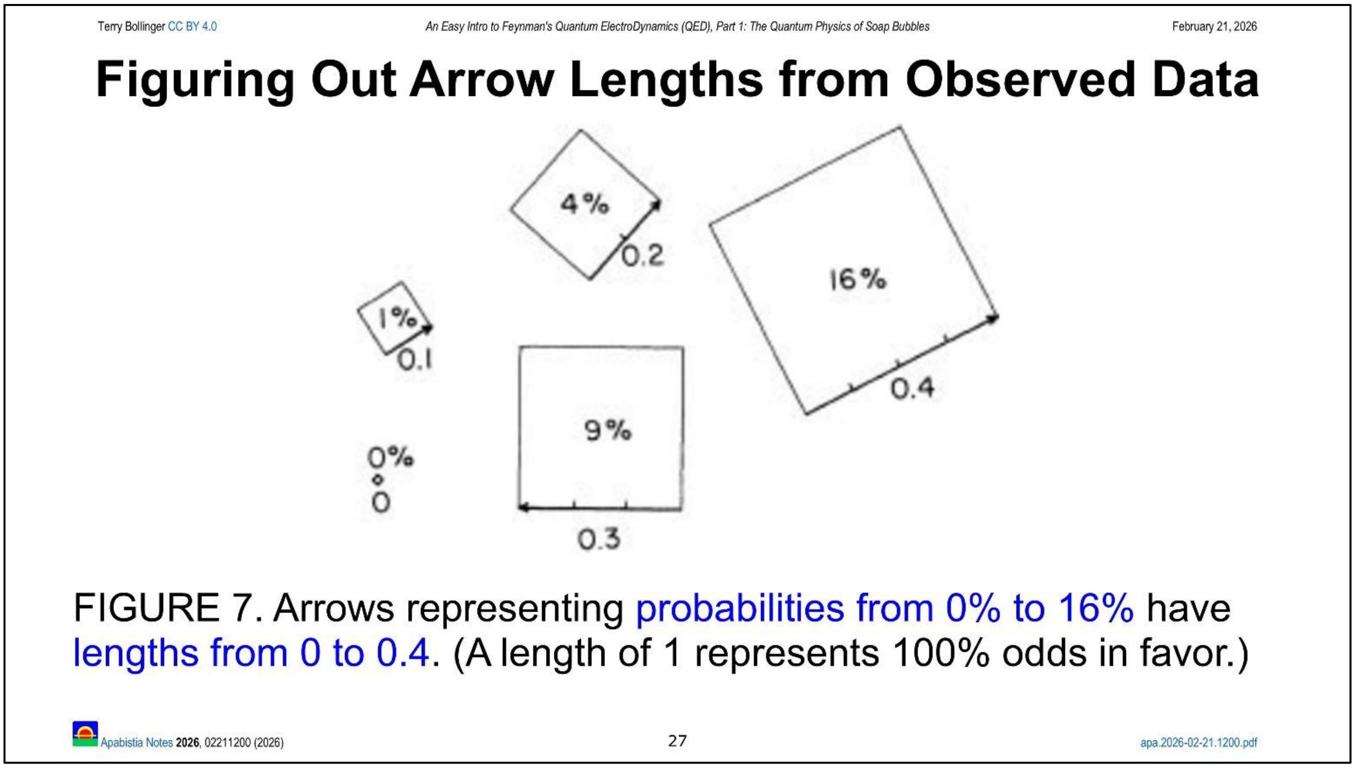
And he even jokes about it, and says, "So, this is *really profound*, folks! I'm gonna *draw little arrows on a piece of paper*. That's how I'm gonna *solve this problem!*"

But his point was serious! He was saying that, yeah, there's a lot of math you can associate with this, and Feynman had *no problem* going *very deep* in the math to do this as a workable problem, to give actual probabilities. But he *would not back off* from the fact that the actual mechanism is nothing more than drawing little arrows on a piece of paper.

Now, the arrows have one property: They can never be longer than 1. *One* is the maximum length of these arrows; 1 represents 100% probability. Then you go down to 0, which represents 0% probability. *In between,* you use a square root, so it's not directly proportional.

When I first made these slides, I even made that mistake — it's easy to fall into that error. The *length* of this arrow he draws is *not* the same thing as the probability. It is the *square root* of the probability.

So, for .04 (4%), you get a much *longer* length for this arrow, which is 0.2 — 0.2, always out of a maximum length of 1.




38:52 So, he found that *that* allowed him to start representing all these probabilities using little arrows.

And the arrows have direction! So, you have different *angles* that they can go at. So, he started coming up with these little *squares*, and the squares give you the probabilities. The *total sum* of all of these probabilities for any given photon is always going to be 1.

So, essentially, he's breaking the probability of finding the photon up into these little areas. The *areas* add up to 1. But the *lengths* of the arrows *don't* necessarily add up to 1. You have different combinations, but you always have this relationship.

So, you have this nice *simplicity* in how that goes.

Terry Bollinger CC BY 4.0 An Easy Intro to Feynman's Quantum ElectroDynamics (QED), Part 1: The Quantum Physics of Soap Bubbles February 21, 2026

## Adding Arrows by Placing Them Head to Tail


FIGURE 8. Arrows that represent each possible way an event could happen are drawn and then combined ("added") in the following manner: Attach the head of one arrow to the tail of another — without changing the direction of either one — and draw a "final arrow" from the tail of the first arrow to the head of the last one.

Apabistia Notes **2026**, 02211200 (2026) 28 apa.2026-02-21.1200.pdf

39:34 Feynman added *another* rule to these little arrows.

Remember, I said that two different things were going on with that photon going through the glass: You have the *first* reflection on the *first* surface, and you have the *second* reflection on the *second* surface.

What Feynman said was, "Well, each of those arrows has one of these *probabilities* attached to it, which you can actually *measure*. So, there's a probability of the photon reflecting from the *bottom*, and there's a probability of the photon reflecting from the *top*.

So he would *add* those arrows and come up with a *final* arrow. So the final arrow would then say, "Okay, if I add *this* one *this* way, and *that* one *that* way — and these are *arrows*, these are not just sums; these are actual *directions* — what is the *direction* of the final arrow?" And then, from the length of that final arrow, I can get a final probability.

So, this is an *oddly simple* way of doing math. He's just saying, "Take the arrows. The arrows have direction. If you square the arrow, you get the probability. Or, if you take the square root of probability, you get the length of the arrow (but not the direction; that is lost). Either way, you can (partially) go back and forth between these two forms.

But when you put them into the *arrow* form, and you start stringing these arrows together, you just add one more arrow by placing it at the end of the last arrow.

There are all sorts of nice mathematical ways of doing this, but the simple way, graphically, is just this: You just shuffle the arrows around, put the X over here, and put the Y over there. The X arrow would be the reflection from the first surface, and the Y arrow would be the reflection from the back surface. And then you wind up with this final arrow.

So, now, if you’re looking at this, the other question you *should* be asking — that you *need* to be asking — is, “What’s determining the *direction* of these arrows?” Because a probability is just a number. It has no *direction* to it! So where are all these *directions* coming from?

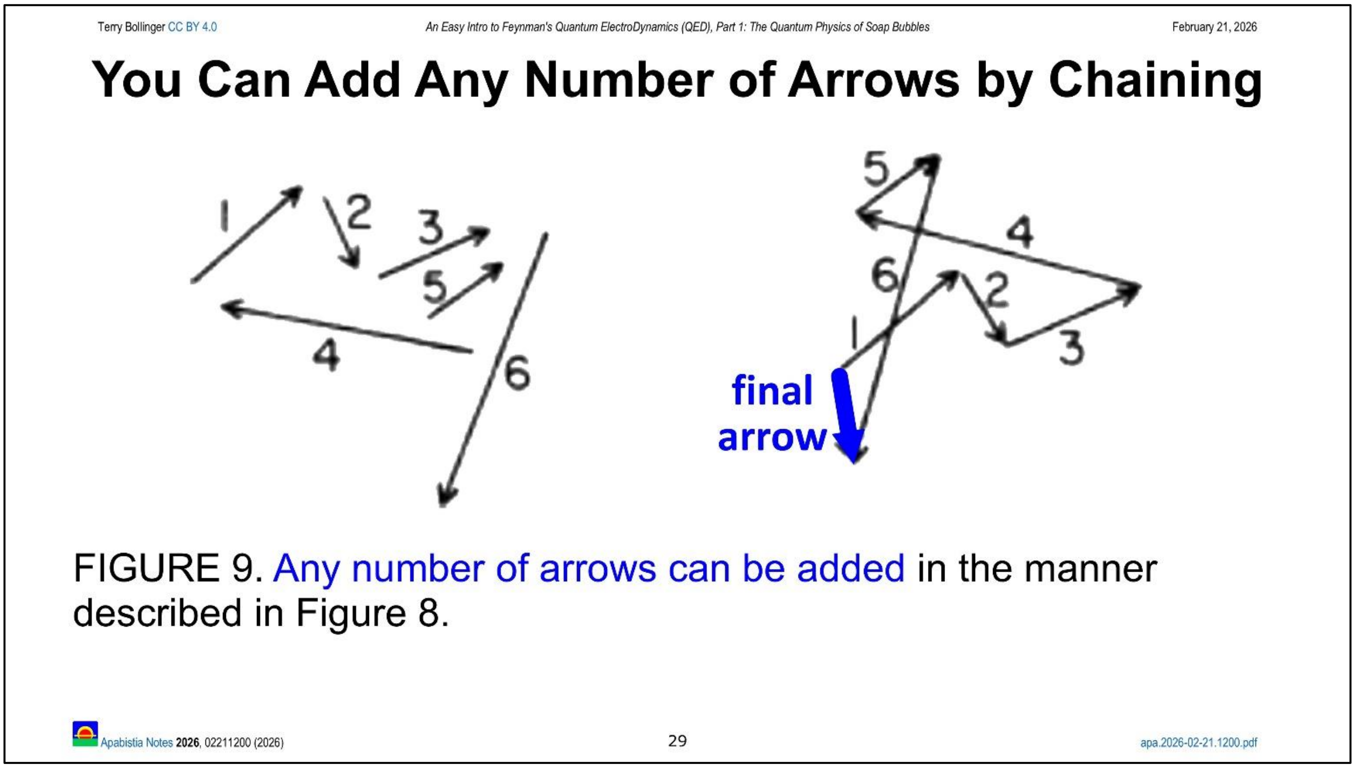


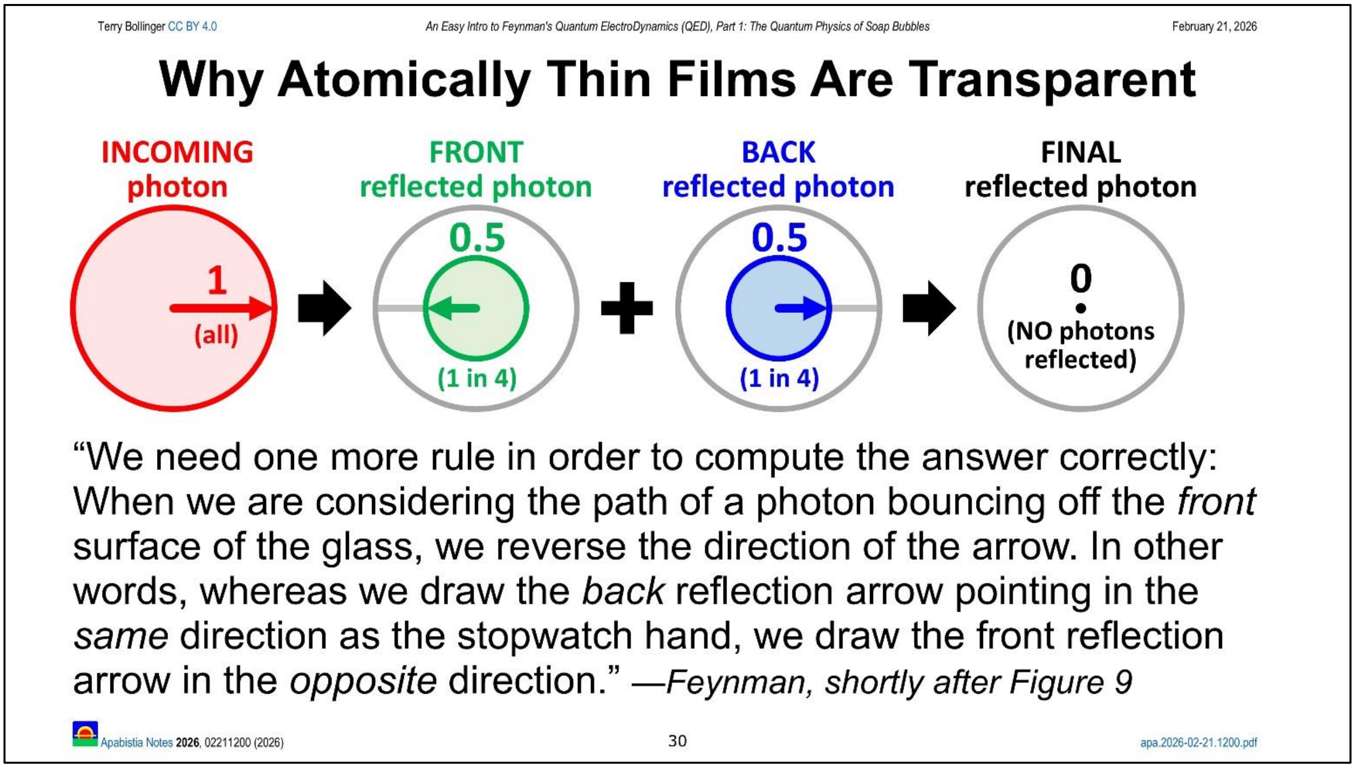
FIGURE 9. Any number of arrows can be added in the manner described in Figure 8.

41:26 But before I get into that, I should point out that you can *keep doing this*. It’s *not* just a *one-time* thing. You can have a *whole bunch* of these arrows!

You can have a reflection event from going through, for instance, a large diffraction grating (such as a hologram), or if you’re going through *layers*. You know how, when you take out a roll of Mylar wrap, how it looks *shiny*, it looks like a *mirror*? That’s what’s going on there. Each one of those little layers of that roll of wrapping is adding its *own* little arrow. And by the time you get done with that, you can wind up with a pretty good mirror; you can wind up with something that’ll reflect light quite well.

That’s what *this* kind of arrow addition, this kind of situation, represents. You have first layer 1, second layer 2, third layer 3, 4, 5… on it goes, and each of these would be different thicknesses of a layer. So you have this nice little addition property — but you always *wind up* with just one final arrow!

And what does that mean? It means you always wind up with one final probability: A number telling you *how likely* it is for light to be reflected.




42:30 Now, a slight tangent — though this is not so much a tangent, but just trying to explain this point a little bit better.

Feynman notes that there's an *additional* rule, and this has to do with materials. It's not something that he gets into, and it's not something you need to know the details of. But it's very important for understanding the *actual* examples of thin films, such as in your no-glare glasses. The rule is that the direction of one of these reflection arrows gets *reversed*.

So, he just starts and says, "I've got an incoming photon. It doesn't matter *where* you point that photon's arrow; you can point in any way you want to. That's the arbitrary nature of what they call the *phase*. But once you *set it*, you have to stick with it. You have to say: 'Okay, I set my arrow at 3 o'clock. And I have to stick with it, and then I have to start *altering* that 3 o'clock according to certain rules.'"

And the first rule is that when you reflect from the *front* surface, you *reverse the direction* of the arrow, as well as reducing its length. Now, I've intentionally used .5 here instead of .2, just because it works out a little easier graphically. It's kind of hard to squish it down there to the .2, but it's the same idea.

So, Feynman's point, and he mentions it in all these slides, is that the *first* one goes *backwards*. And then the *second* one, when you reflect from the *back* surface — because you're going from a *denser* medium (glass) into a *lighter* medium (air) — it turns out that the photon arrow *keeps the phase* (direction). So, you get the same phase — the same direction — as the original arrow of the photon that came in. So that arrow points *this* way.

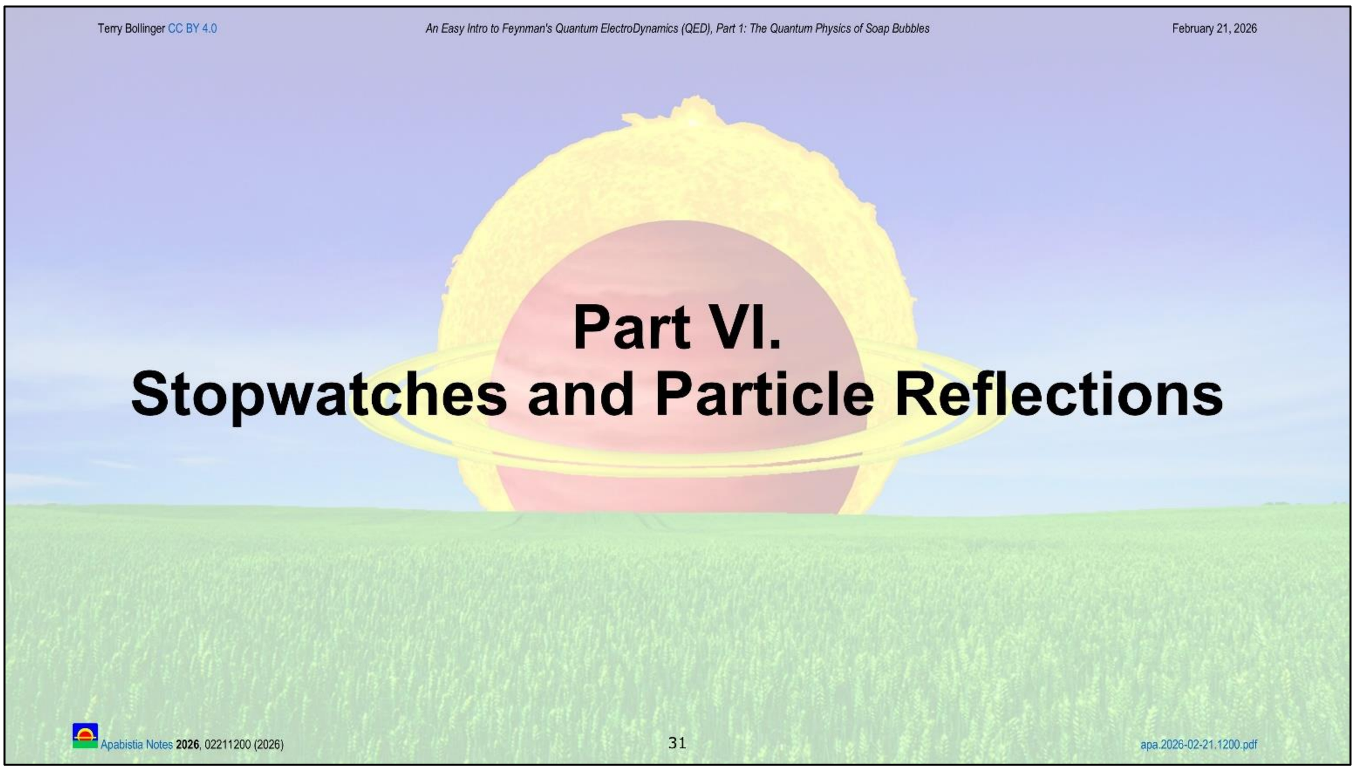
Okay. Well, now look at this. If I take *this* arrow, the *green* one, and I stick it over *here*, so *green* goes *this* way, and then the *blue* goes *this* way — it doesn't matter which order you do it, in this case, you come out with *zero*. There's no vector. They *cancel each other out*.

So, what this is saying — if you add this rule that Feynman talks about shortly after Figure 9 — is that for an *atomically thin film*, even if it's a *highly* reflective material, *you don't get a reflection* — you don't get *much* of a reflection.

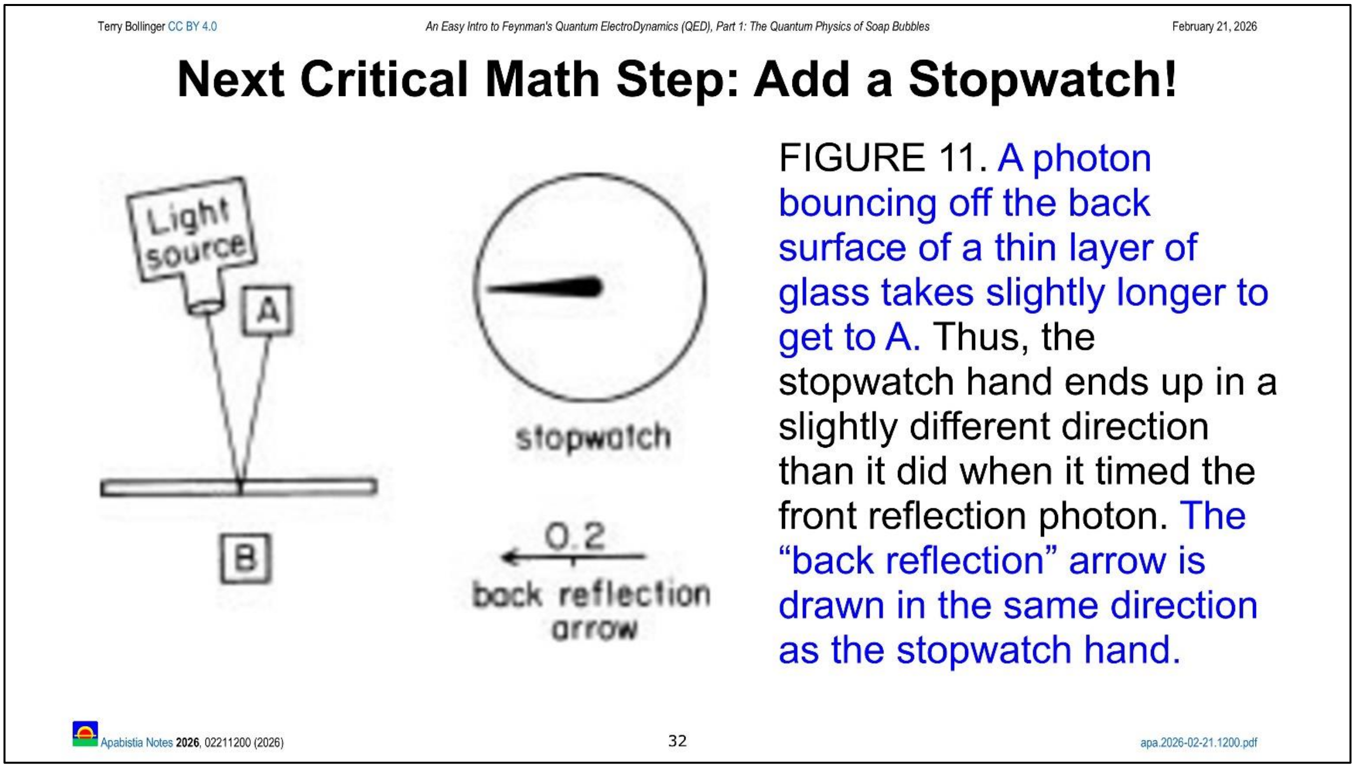
Why? Because the *arrow* that you started with is *reversed* for the *front* reflection, and *preserved* for the *back* reflection, and they are *so closely opposed* that they wind up canceling.

Have you ever looked through gold leaf — through very thin films of gold? If you do, you get this effect. You actually can see *through* them. This is part of why you can do that (at least for some frequencies, mostly around green). So, even a *highly reflective* material like gold leaf will lose its ability to reflect photons if you make it *extremely* thin.

Gold leaf is fun stuff, because it's *so* malleable that you can just *squash* it into layers *so thin* that you actually start seeing this quantum effect kicking in.




45:32 Stopwatches and particle reflections.




45:34 *Stopwatches!* How do those arrows make their different changes in direction?

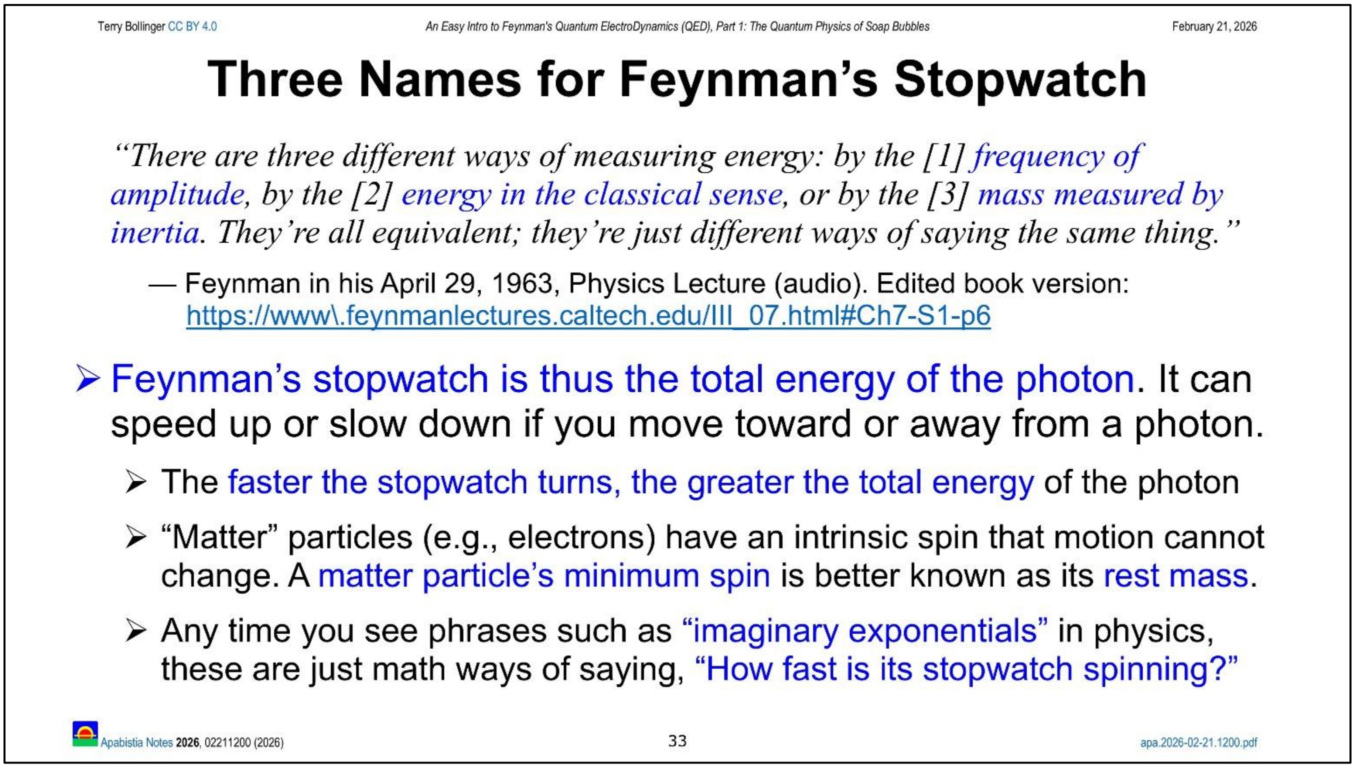
I gave you one example of how an arrow changes direction, which is that if you reflect photons off a *front* surface, from a *lower* optical-density medium (air) to a *higher* optical-density medium (glass), you get a *reversal* of arrow direction.

Okay, so that's one change. That's just a reversal. How do they transform in *general*, though?

Well, it turns out that what you need in this case — and again, Feynman is intentionally humorous about this — you need… a *stopwatch!*

That's the advanced mathematics that you need to understand this: a stopwatch! You need a dial with an arrow that rotates. *That's it.* You don't need *all sorts of fancy equations, integrals*. You get the integrals later, but to understand the basics, *you just need a stopwatch*. You just need a little *stopwatch* whose hand (the arrow) *moves* and *changes* as the photon moves through space.

So, a straightforward idea! We've got *two* transformations on the stopwatch: *Reflection* will either keep the direction of the arrow the same, or it will reverse the direction if it's on the front surface. But when you are *moving through space*, it simply *turns the hand* — the arrow. And the hand turns at *different rates* for *different frequencies* of light.




46:54 Three names for Feynman's stopwatch.

Feynman talks about this in his lectures. I like the audio version. The audio version often has little tidbits that you don't get in the printed version. Feynman was *incredibly* careful in his statements, and often, he said things that even the editors of his lectures *didn't always quite catch* what he was trying to say. And they would misunderstand a little bit. So, it's often good to listen to the audio versions of his lectures, and these are available.

You can see that Feynman defines the concept of energy in three ways. First, you can have energy in the *classical* sense. A photon is pure energy; it has no rest mass or anything. But secondly, you also have mass, as measured by … gravitational mass, so that's another way of measuring the mass, the energy of a photon. This is a good old $E = mc^2$, nothing more than that. But the third one that people miss — the one that's very easy to miss — is that there's another definition of mass, which is just *frequency*. Some people would call this the *quantum frequency*. Feynman calls it the frequency of amplitude — that little arrow we've been drawing, the little arrow that goes out.

The *faster* the arrow turns, the *bigger* the mass. How's that for a complicated relationship? So *you*, sitting where you are, you have an amplitude. You have a frequency. It is *unbelievably* high because you are a *combined mass* of a whole bunch of things, and there's a frequency associated with that *combined* mass that is *independent* of the individual frequencies. And it's *hard* to measure… *very hard* to measure for large objects. But *not* impossible! People can get almost up to *dust-sized* particle ranges these days when measuring this special frequency. It shows up in double-split experiments, for example.

So, there are *three ways* of defining mass and energy. Mass-energy, same thing, $E = mc^2$. But also, the *quantum frequency*, which shows up *even in soap bubbles*.

So, the stopwatch is the total energy of the photons, so guess what? *Blue light* has a faster stopwatch than red *light* — about twice as fast as it goes through space. They're both *winding out* at different rates.

Matter particles also have the same thing. That is, the total energy of the particle for an electron is *also* a frequency, and the frequency works the *same way*. It interferes in the same way; it follows the *same* rules of interference.

There's a *catch* with an electron, though, and the catch is this: The *electron*, unlike the *photon*, has something called *rest mass*. And what it means is that you *cannot* get rid of this frequency that is attached to that particle. If you have an electron, if you have this rest mass, you have this inherent frequency, and you can't get rid of it.

Now, if you look in physics literature, and you see things like *imaginary exponentials* and some complicated math, those are not trivial. There are a lot of interesting things that go on with those ideas. But, as it turns out, for imaginary exponentials — which look *really wild* — there is *no need* for you to say, "Oh, this is a concept I'll *never* understand!"

*Yes*, you can *understand* it! It's just a *stopwatch!* It's a *way* of expressing the stopwatch. In many ways, the stopwatch is even a little *more* accurate. That's because the stopwatch has *no* differences (e.g., 1 versus *i*) in arrow direction. The stopwatch, in contrast, is completely *even* all the way around — whereas with imaginary exponentials, you do have some structure (e.g., 1 versus i) that's actually a little bit redundant.

So, don't let the terminology throw you off sometimes. Simple things are often beneath these other ideas. And the idea that "mass-energy is a frequency" is an *extremely* helpful idea for understanding *any* version of quantum mechanics. We may *express it* in complicated ways, but you *don't* have to have that full understanding to get the concept out of it.

Terry Bollinger CC BY 4.0 *An Easy Intro to Feynman's Quantum ElectroDynamics (QED), Part 1: The Quantum Physics of Soap Bubbles* February 21, 2026

# When the Time Change is Small, So is Reflection

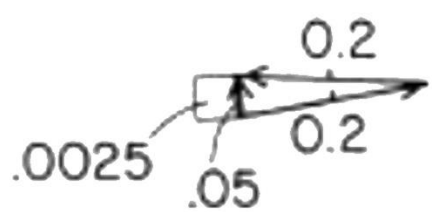



FIGURE 12. The final arrow, whose square represents the probability of reflection by an extremely thin layer of glass, is drawn by adding the front reflection arrow and the back reflection arrow. The result is nearly zero. [TB Note: Recall that the stopwatch arrow from the *front* reflection — the bottom 0.2 arrow in this figure — has flipped 180° from that of the unchanged arrow direction from the back surface.]

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51:07 So, why do you get a *small* reflection in many cases?

If you've got a *very thin* glass, you get that cancellation effect. I've already talked about this. I gave a more extreme example: If it's *atomically* thin, this will go pretty much to *zero*, so you get almost *no* reflection.

That's why gold foil transmits some light. You can see this marvelous little ability for the gold to actually *transmit* some green light, *because* it's so thin. And there's a connection there. Gold is *extremely* reflective — it's one of the most reflective media that exists! And *yet,* if you can pound it into a thin enough sheet, you can actually see *through* it.

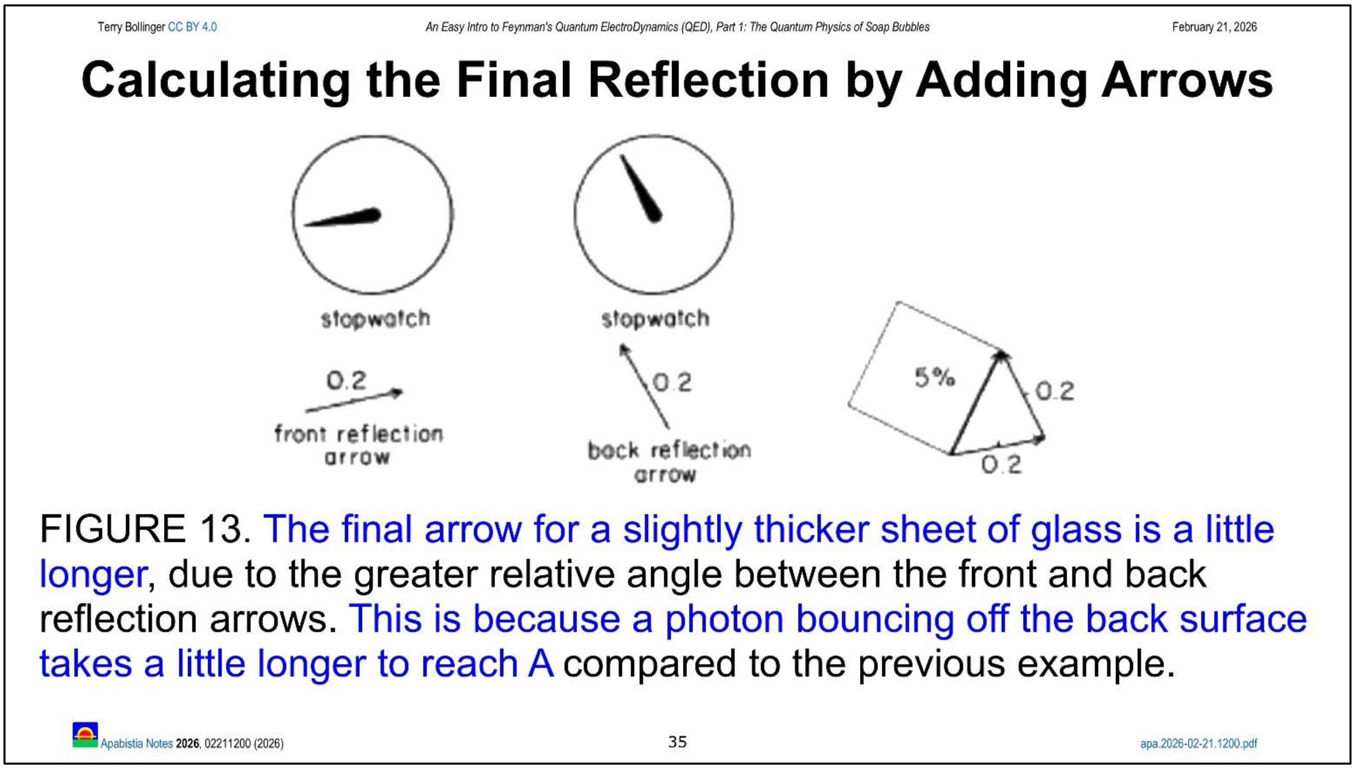
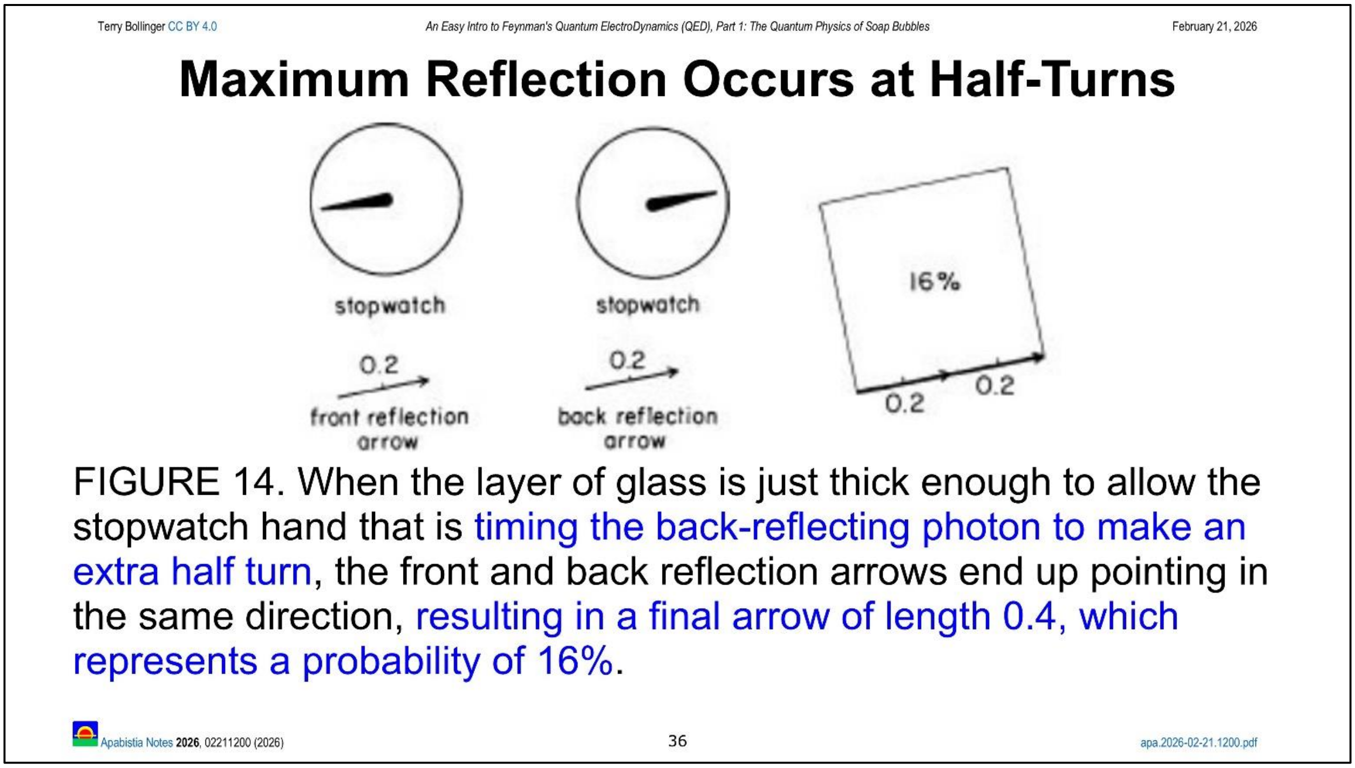


FIGURE 13. The final arrow for a slightly thicker sheet of glass is a little longer, due to the greater relative angle between the front and back reflection arrows. This is because a photon bouncing off the back surface takes a little longer to reach A compared to the previous example.

51:49 The way you get your final probabilities, then — and this goes back to that issue I said earlier — you've got these arrows, and the arrows' lengths are just the square roots of probabilities. But where in the heck do each of the *arrows* come from?

Well, they come from two things. You get *reversals* due to reflection, and you just get *rotations*, because they are going through space. The photon is traveling, *zipping* on through there, so you want to *calculate* how fast it's going to turn for a certain length. And *different photons* are going to have *different amounts of rotation* as they go through a film.




52:26 The *maximum* reflection occurs when you get these totals of one half-turn for an arrow that travels twice — first forward, and then reflected back — between the front and back surfaces of the film. That is because, in that case, the front and back reflection arrows then *add up*, and you get a stronger reflection back toward the source. That's where you get the 16%.

So, if you have that case of a film thickness that allows the photon reflecting from the back surface to rotate one half-turn total after reflecting and returning to the front surface — that is, one quarter turn for each trip forward and back through the film — then the reflected arrow that you get from the *back surface* matches the "instantly" reversed reflection *arrow* from the *front surface*.

That is because you have one "instantly" reversed arrow from the front reflection — the one that is half out of phase, a reversed arrow. You then *flip* the back reflection by a total of half a turn due to the forward-and-back travel time, and wind up having the *same* reversed direction for both arrows.

So, in terms of reflection, your traveling through the film is *undoing* the direction-reversal "damage" done by the front reflection. The front reflection *always* reverses the reflection, but if you accumulate *exactly one half of a turn* for the back reflection, the two different sources of half-a-turn "damage" match, and the added arrow length goes to a *maximum*.

And, suddenly, you get a much *bigger* glare — you get a *worse* glare. This is your *worst-case scenario* for glasses! This is what you *don't* want to do…

Sebastian, did you have a question?

53:20 **Sebastian Zając** (SZ): Yes, I just have one remark. Maybe it will change your talk. But please, do not describe this arrow as the square root of probability, because it's not the same thing. The square root of probability means you are taking the square root of a real value that ranges from 0 to 1. However, for quantum amplitudes, you need a vector. Taking the square root of a scalar probability from 0 to 1 gives you only two directions, which are the plus and minus roots. Plus-and-minus thinking is not enough to describe what is happening here. So, you need more complicated values for these squares in the figure than just a scalar 0 to 1.

54:06 **Terry Bollinger** (TB): Yes, I agree completely with that.

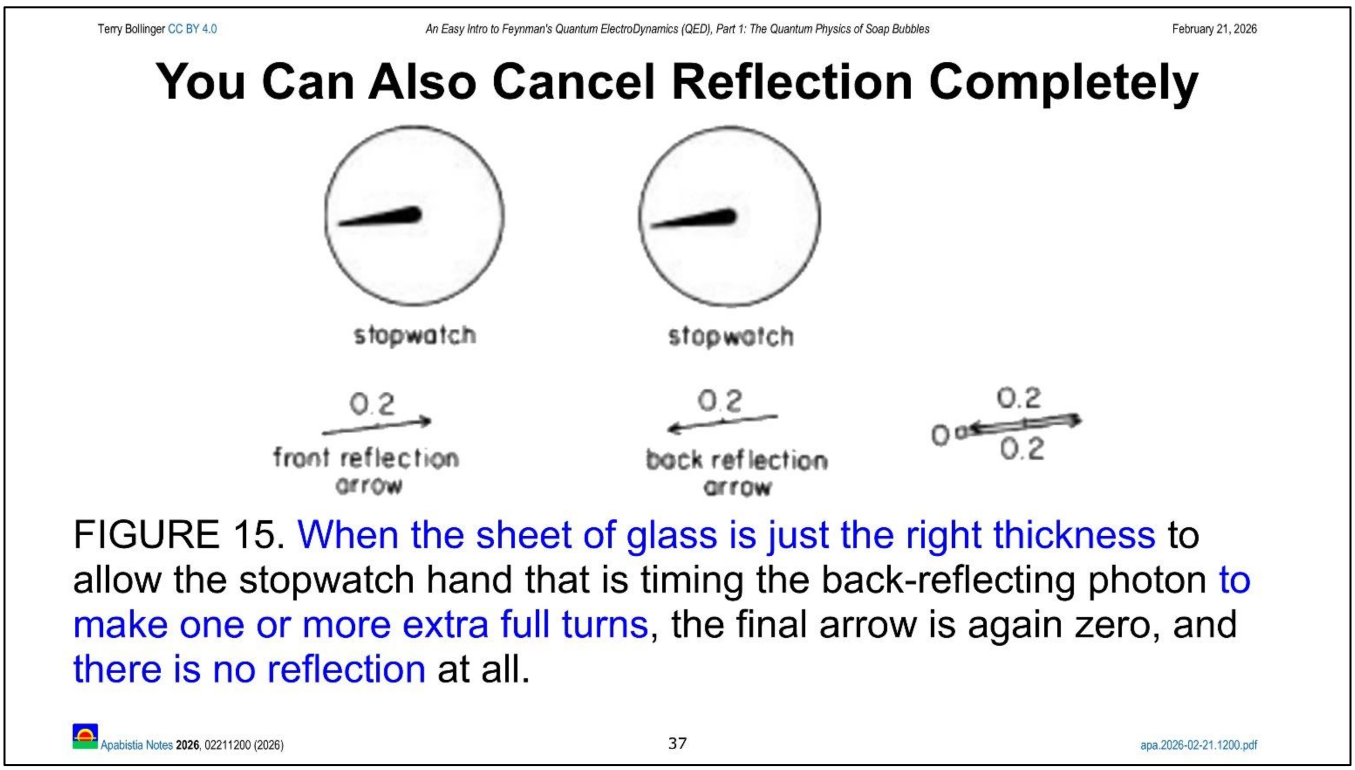
54:13 SZ: We cannot use probability as the main thing here. The main difference is that this square of the amplitude is *not* a probability, and the probability is not really "only" the square of an amplitude.

54:28 TB: No, it is not. I agree completely. My point was that when Feynman was using his amplitudes, the amplitudes were what he viewed as fundamental.

So, the idea that the length of the amplitude has a relationship to the probability is only the starting point from experiment, where you observe a probability. You get a percentage of how many of the photons get reflected.

Feynman's whole point was that the amplitude is *far* more fundamental than that, and you *cannot* understand how these things behave by looking only at the probabilities. You have to strip away the structure to get to the probability stage. So, I agree completely.

55:05 TB: Returning to the slide, maximum reflections occur at *half-turns* of the arrow reflected from the back. By choosing a film thickness that instead results in *one turn* of the arrow reflected from the back, you can also cancel reflection completely.




55:08 The simplest case is if you have an atomically thin film, then you get a full cancellation. I've already discussed this case earlier in Slide 30, *Why Atomically Thin Films Are Transparent*. First, you have that reversal at the front. You get the little switch shown here in the smaller arrow below the bigger, more obvious arrow, which, somewhat confusingly in this figure, shows the *incoming* photon arrow, not the front-reflection arrow.

You also get the *back reflection* arrow, which goes in the same direction as the incoming photon. Again, you should look at the small arrows below the big arrows and dials, though, for the case of the back reflection, the big and small arrows go the same way.

And they cancel out to 0, which is the example I already showed in Slide 30. I'll go back very briefly to that slide, just to show it again, since that's what the arrow discussion is all about. So, looking now at Slide 30, for an amplitude of .5 in length — which is a 1-in-4 chance of a photon getting through — you get a complete reversal of arrow directions, and you wind up with no photons.

So that's exactly the kind of case that Slide 37 is talking about.

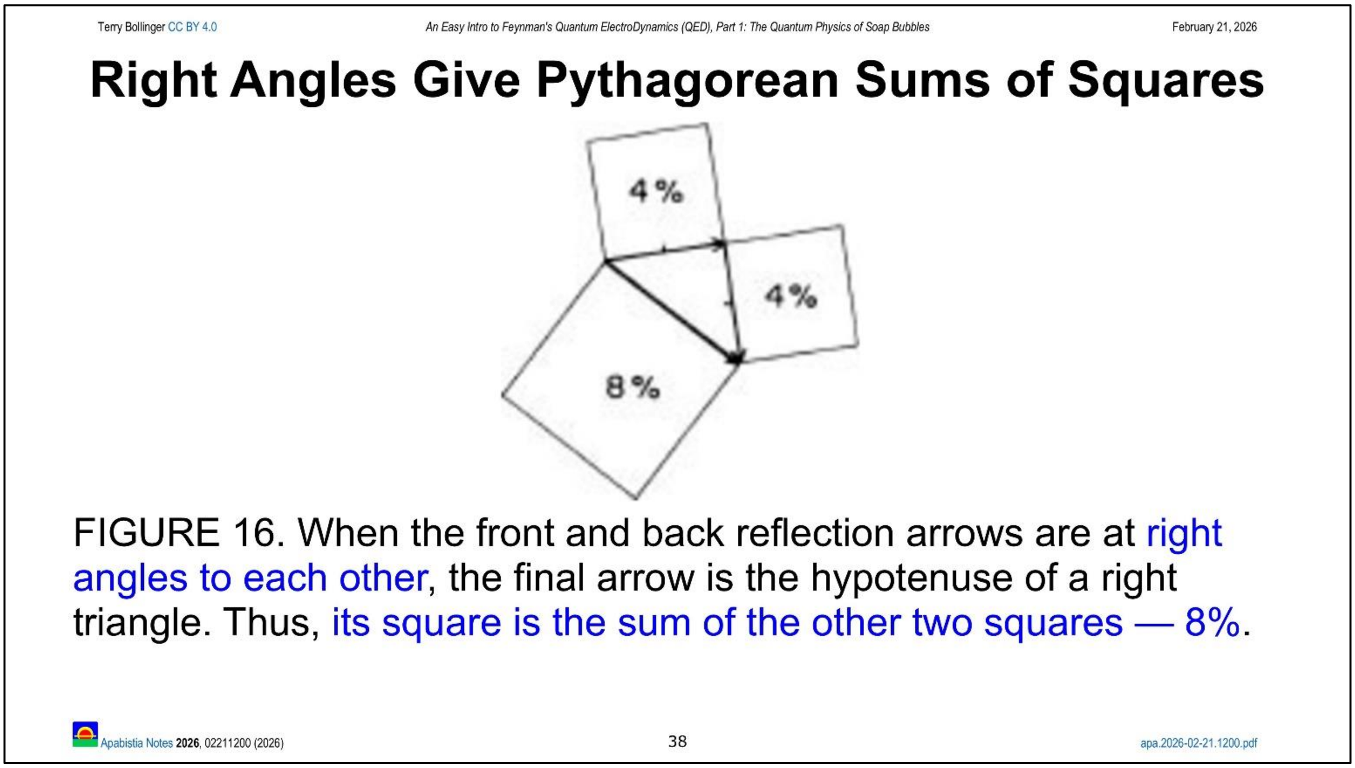
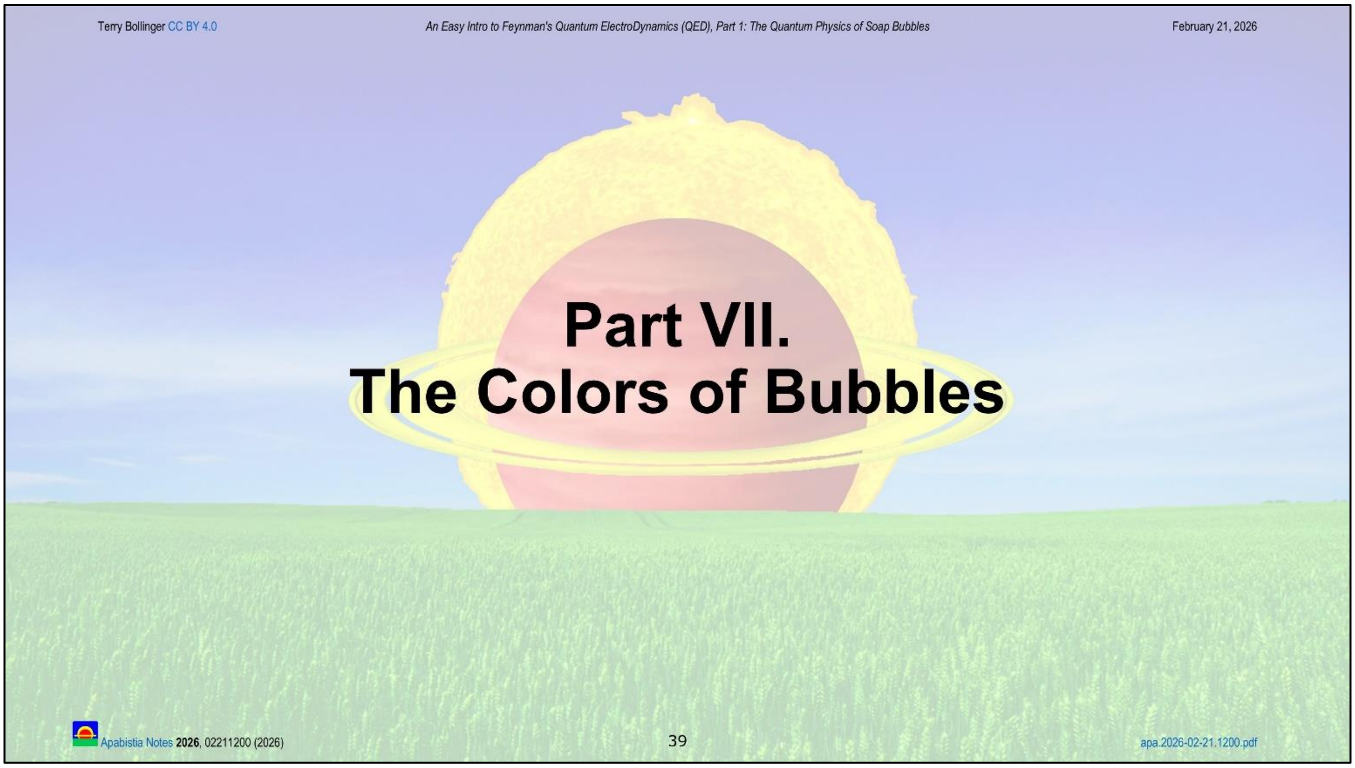


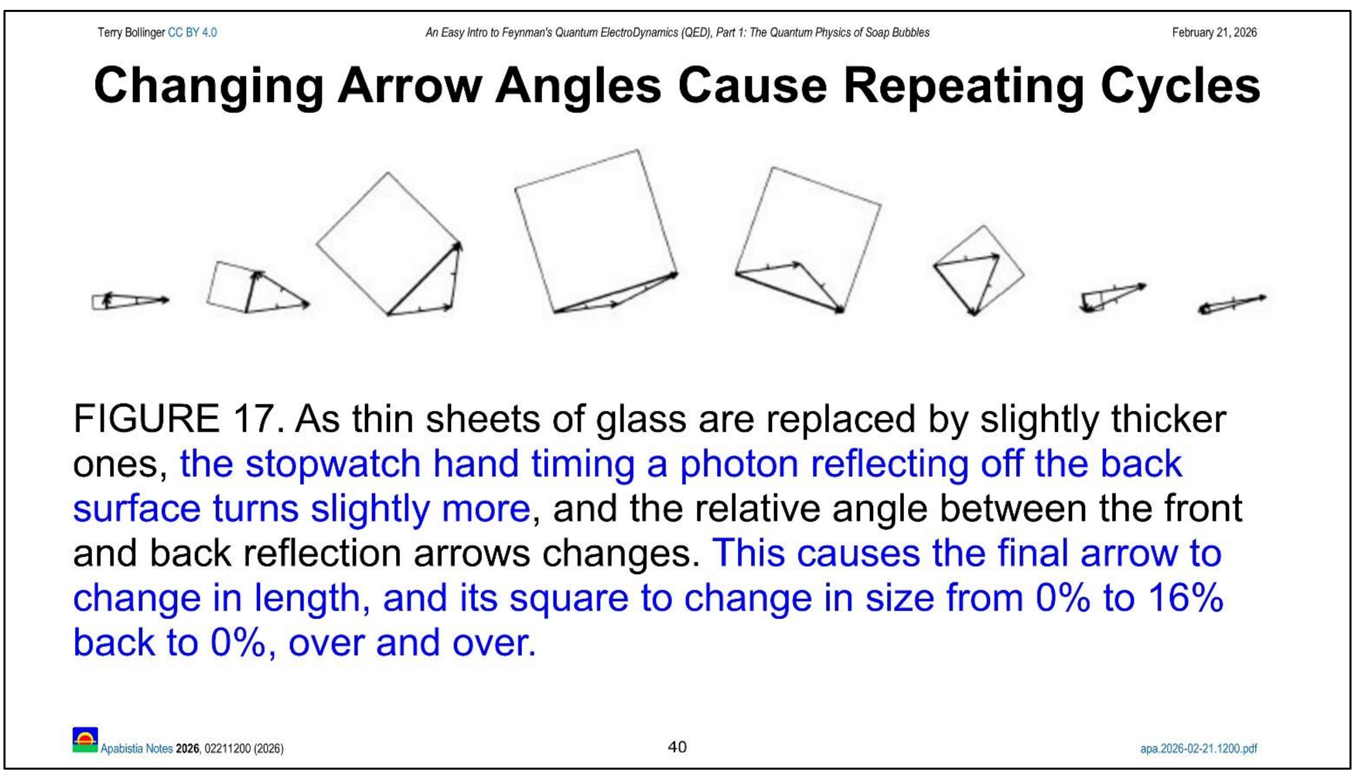

FIGURE 16. When the front and back reflection arrows are at right angles to each other, the final arrow is the hypotenuse of a right triangle. Thus, its square is the sum of the other two squares — 8%.

56:02 Now, notice that there are lots of arrow *angles* that are involved with all of this, with a new arrow for each new step in the progress of the photon. You've got angles with the arrows, and a way you add these arrows — because you're just adding them end-to-end — you wind up with things like the Pythagorean Theorem in how these things add together.

So, it's a simple form of math, and the Pythagorean theorem is a particularly interesting case of how these amplitude arrows add.




56:33 The *colors of bubbles! Why* are those bubbles *colored*?

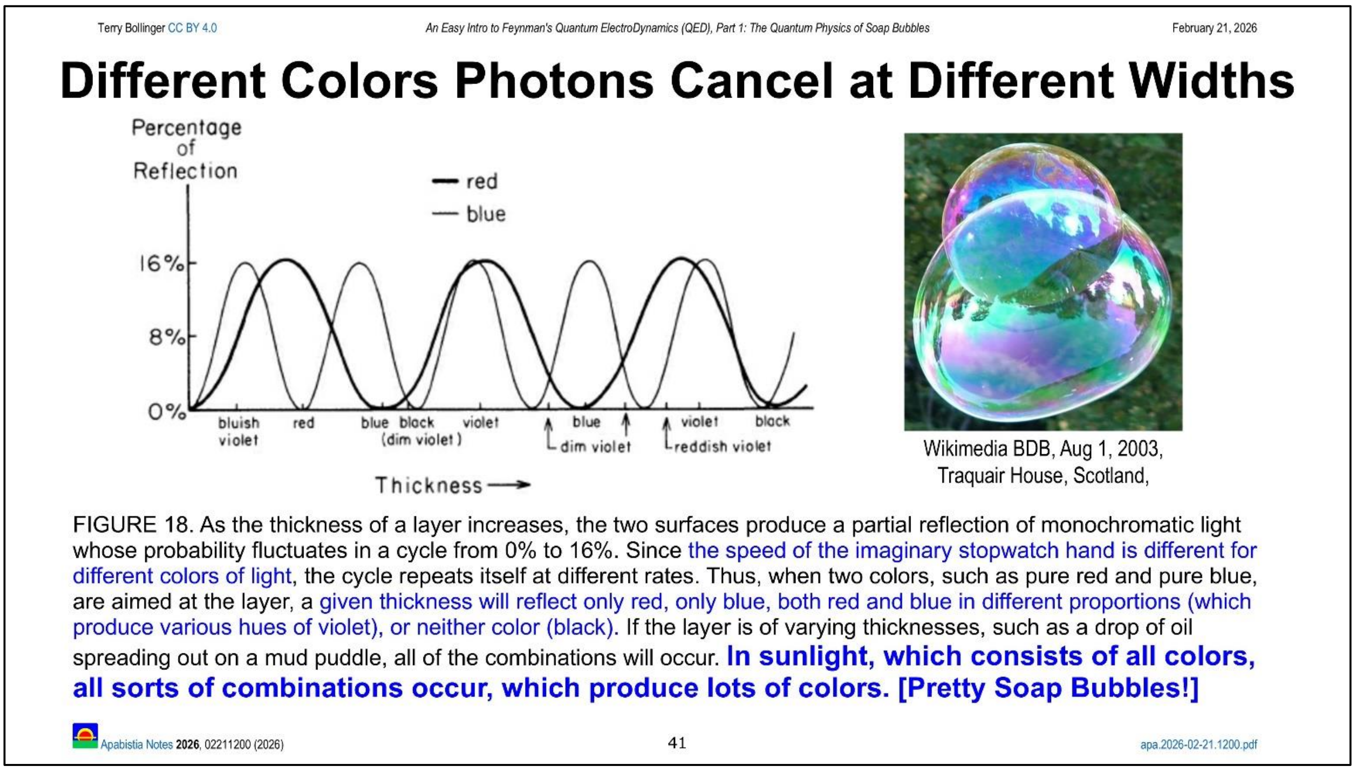



56:40 *Well*… part of the reason is that you have this *cycling effect*.

You have these *amplitudes* that are *rotating* at different rates. So, as you go through this left-to-right sequence on the slide, you can see how the *probability* of a photon reflecting is *transforming*. And again, this probability is just a *scalar*. If you want the *real* structure — if you want to understand what's really going on — you *have* to go to the amplitude. As Sebastian said, you *can't* just take a "square root of probability." That doesn't tell you the story. You *have* to look at these rotating vectors — at this much more *interesting* and *structured* concept than just having a probability.

But what *happens*, as these amplitudes diverge with thicker and thicker layers (see this cycle?), is that you're going through cycles. You start with almost zero, then it gets a little bit larger — and again, the square represents probability — and then, it shrinks back down to zero.

Well, doesn't that sound *familiar*? *Yes!* That's the *0-to-16%!* So, this idea of using *amplitude arrows* that *rotate* as they go through space gives you an explanation for why you are seeing those *cycles* — the same cycles that baffled Isaac Newton.




58:00 *And*… maybe even *more* importantly — I'd say it *is* more importantly — *different colors* have *different speeds of rotation* of the amplitude. This corresponds, pretty much one-to-one, with what we think of as the frequency of the light. Blue has about twice the frequency of red, so you get about twice the rotation speed as red. So, the *blue* winds up *rotating faster* as it goes through that film. And, as a result, there are different bubble levels — different film thicknesses — where it *peaks*.

So you have the *blue* peaking *here*, and you have the *red* peaking *here*. And guess what? *This* peak gives you something like this: a *purplish* color, because you're getting *red* and *blue* combining. (Obviously, we've got some *green* in there, too, to throw some more confusion in!) But you keep getting these different *peaks*.

So, for different *thicknesses* of the bubble, you can actually wind up with *repeats!* You can see the *same color* playing *over and over again* as the bubble gets *thinner*. If you've ever seen a bubble that is resting on a surface —

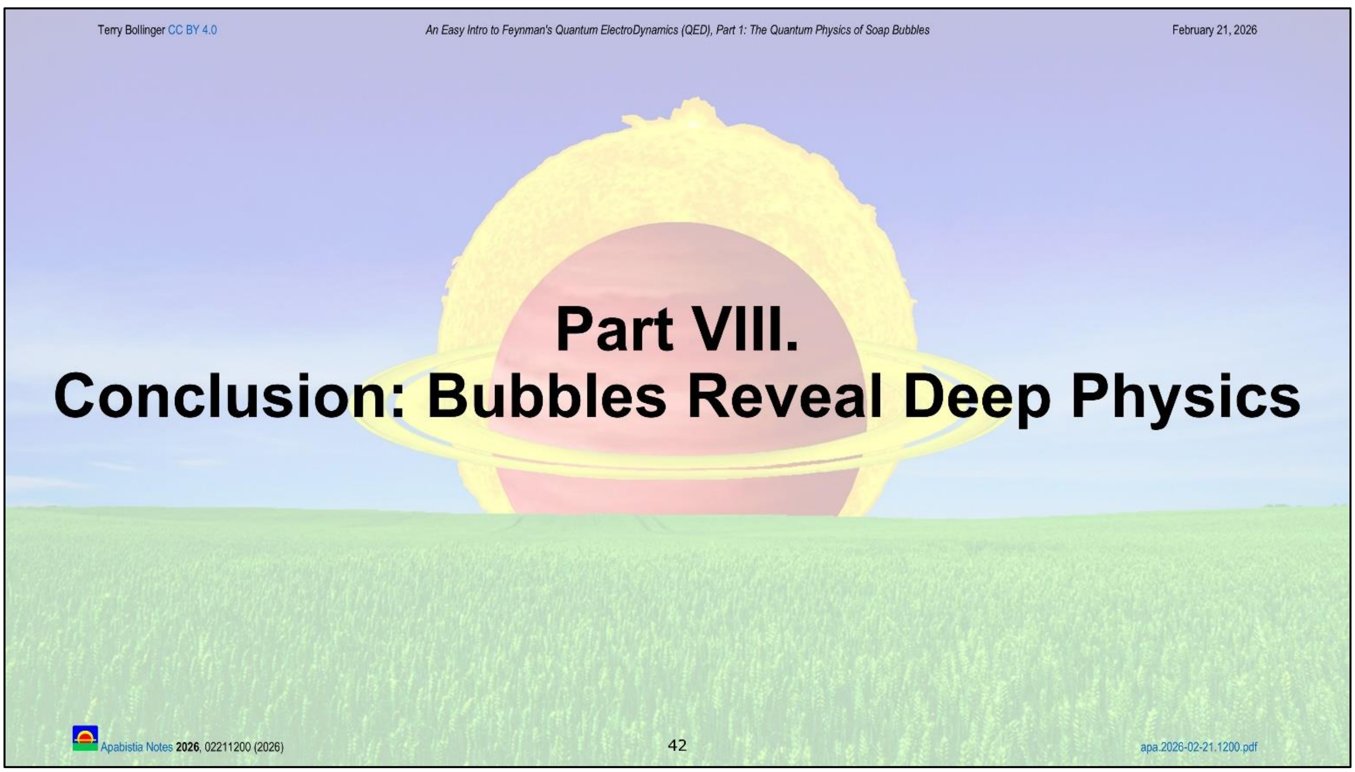
and this floating bubble shows the effect a little bit, since there's a little bit of gravitational pull even as it floats — there's a little bit of *layering* of the colors.

So these bubbles — vertically stratified bubbles — will show these different layers of repeating multi-color peaks. So, you can actually *watch* the different peaks where the *red* and the *blue* are reaching their maximum probability of reflection, and giving you *colors* that play across the spectrum. These are *never* rainbow colors, though! These are more interesting *mixed* ranges of colors — e.g., purples — just different, *strange* little combinations of how the light frequencies might add.

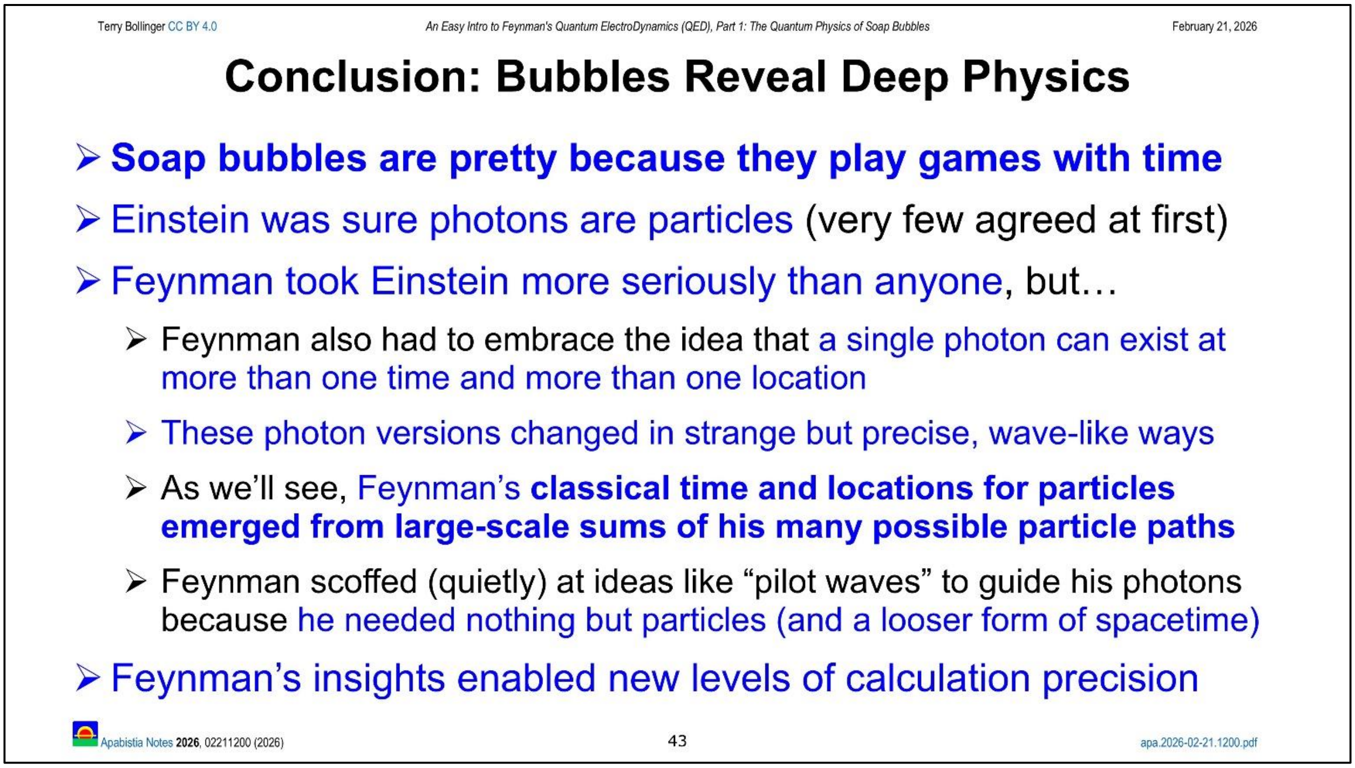
Sunlight gives you *all sorts* of color frequencies, all peaking at different times, so you get these really beautiful bubbles. But, think about this: *Where's that color coming from?*

It's coming from *quantum mechanics!* Not just quantum mechanics: It's coming from a form of quantum mechanics where you have to *play some games,* even with the concept of how a particle sees itself *over time*.

So the photon, as a particle, is playing *two roles* at the *same time*. And *experimentally*, it *has* to have time to *complete that*. It *has* to have some *temporal uncertainty*, as you would call it in quantum mechanics, in order to see this color! Without that, *you won't see any color*. It's as simple as that! The color *depends* on the ability of the photon particle to get a little bit *lost in time*, and look at *reflections of itself*.




[1:00:39](#) Conclusions: Let's wrap this up here!




1:00:44 As I was just saying, soap bubbles are *pretty* because they depend on a level of… what would *you* say?

I'd say, "Some of the most *fascinating* but *simple* things that go on in the universe!"

Specifically, they depend on this idea that there are *amplitudes* associated with *particles*; that these amplitudes *turn*; and that these amplitudes are related to the *total energy and mass* of the particles. All of these are *very fundamental* concepts of our universe. And soap bubbles *show* that, because they *play games* with these parameters — because they play games, *little tiny games*, with *time*. But you can make those games *larger* and *larger* until they start getting *quite* interesting!

So, Einstein thought *photons were particles*. People didn't agree! People *still* don't agree! (chuckle). I mean, we have *so many* interpretations.

If you look, for example, at the *many-worlds interpretation*, it does the *exact opposite!* It says there are *no* particles — it says that *everything* is actually *a wave*. So those two interpretations, Feynman's and many-worlds, are at the *absolute opposite ends* of that interpretation spectrum.

Then you have what's called a *pilot wave*. That's the viewpoint that you have *both* a wave *and* a particle. And again, Feynman *would not* go there! Neither would the people on the MWI, the many-worlds interpretation. They *also* want to have one or the other.

But what Feynman did — that, as far as I know, no one else ever tried — was, he said that, "*Yeah*, it's *particles*… but *obviously*, they are *not* behaving like any particles *we've* ever seen. They have to behave in an *extremely* non-classical fashion." That non-classical fashion then gives these *different images* of the *same* photon, which then *combine together* using this *simple idea* of little arrows that *rotate in time*, and rotate in different ways. And, when you add these rotated arrows together, you wind up getting some very good predictions.

So, when you do this — and this is something I'll get into more in the later lectures — Feynman played enough games with classical time and location that he was very casual about saying that, "You don't get *speed of light* until you *add* a bunch of these probabilities together."

So, for Feynman, there are several places where he says, point-blank, that at small enough scales, *the speed of light doesn't matter!* And, that it's *only* when you add enough amplitudes together that you get an *emergence* of what *we* think of as *classical time* and *classical space*.

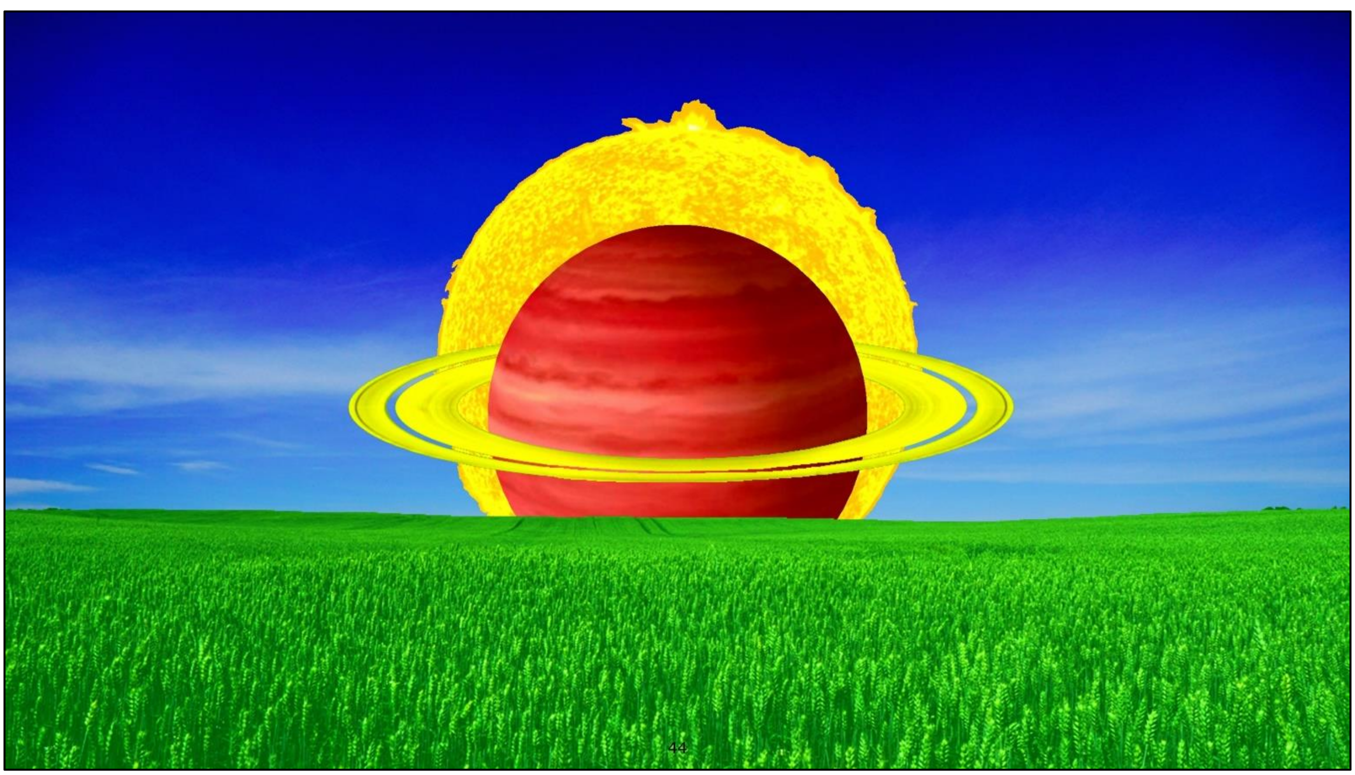
When people talk about *decoherence*, they're talking about some related issues: that when things are interfering with each other *enough*, then you start winding up with situations where there's no way back — you can't go back anymore.

Feynman talks about the same idea, but Feynman does it at a *much* more precise level of detail for *two* particles, electrons and photons, than anyone else. And he does some *really interesting* things with that.

I would argue that one of the reasons why Feynman was able to get a good level of calculation precision was precisely *because* of his emphasis on *simplicity*. It is *so* easy to get into this thing about saying, "How can I make something sound *really impressive* — very *complex*, lots of *integrals*, lots of *this* and *that*?"

*Yes*, if you're calculating it, *you need all that*. *Yes*, that math is *extremely important* for getting the *full* calculational probabilities and descriptions. You have to have that. Feynman *loved* getting into that. He was *always* diving into different kinds of math.

But he *also never* backed off from the idea that beneath all that is *simplicity*. Somewhere, down there deep, something is going on that is just may be as simple as a little clock dial running through space, and giving you whatever you want.




1:04:19 And, with that, I will wrap up this part of my talk about the Feynman QED book.

***Questions and Answers from after the presentation:***

HM = Helen Ma (Team OrionX)
TB = Terry Bollinger
SZ = Sebastian Zając
CP = Caetano Peng
JJ = Jordan Jannone
WS = William Slater

1:04:40 HM: I noticed that George had a question earlier. He asked whether a more formal description of the vector product area might be possible, like Grassmann or Clifford. He was just wondering about this while he was here.

1:04:53 TB: The Clifford algebra and the Grassman algebras, absolutely are interesting, and I think there are better ways to approach some of this. Feynman, I think, was respectful of some of these mathematics.

I am very fond of some of the Clifford algebras. I think they do a nice job of saying that there's more going on here than meets the eye, and you get some interesting connections.

The Grassmann algebras are notoriously a bit more cryptic and cover similar turf. I think Clifford's work is kind of easier to understand. If you've never looked at a Clifford algebra, well… those are neat! They seem to capture some of these properties in a very nice way.

1:05:42 SZ: One remark, Terry, is that our world — I don't know why — is more algebraic than spacetime metrical.

1:05:52 TB: I'm sorry, could you say that again?

1:05:55 SZ: In my opinion — and again, I don't know why — our world works more *algebraically* than like ordinary space with metrics, that is, like how we imagine three-dimensional space and time to work.

So, as you've shown, all of this is more *algebraic* and *mathematical* than our intuition and thinking encourage us to see our world.

1:06:23 TB: Yes. One of the things that to me is just marvelous — and you see it in QED — is Feynman's description of how simplicity emerges from the *complexity* of these interactions. He essentially *drops* all of the usual boundaries of space and time at the lowest levels — and yet, from that, he sees an emergence that looks very *algebraic* — much *simpler*, and really understandable.

One example — and again, this is from slides that I'm not presenting today — there's this interesting case of the Feynman diagrams. When you look at the Feynman diagrams, you can have a situation where you have an electron going through space. Then a photon hits it, the electron goes on for a little distance, and then it gives off a photon again.

This is called scattering the photon, but one of the things that they tend not to emphasize to people when they learn that in physics is that both of those Feynman diagram vertices — the one where you have the photon hitting the electron, is absorbed by the electron and the electron carries it for a while, then the photon comes back out — those two vertices are *physically impossible*. It's what they call "off shell." It has a combination of momentum, mass, and energy that cannot happen in the classical world, where it's impossible, that is, off-shell.

But in the quantum domain, it can happen. And this is the marvelous thing about that, since this is a very standard thing in Feynman diagrams. Yet people don't even realize that the interactions — the little vertices they show — *cannot happen* in the classical world. They're not possible! And yet you have simple algebraic-type structures that emerge from that after you go through that. So it's a fascinating connection between simplicity and algebra.

Any other questions?

**[The text below this point is still a raw, unedited, auto-generated transcript. Expect errors!]**

1:08:33 SZ: Maybe one thing, what do you… what's… because this picture is very nice, but of course, this is trying to classify… classical view of how we can understand these strange properties of lights, and for electrons, this book is… Of course, not so deep, like, for photons, but, QED is just a quantum field theory, so at normal physical level, so… What do you think? About these kinds of theory, too. To represent any kind of interaction. Because, as I said, okay, this… what you… what you've shown, and how Feynman showed it, it is just… For pictures, and to understand, okay, there is something strange, but we can imagine that this is vectors, and this is face. If we look at that, we can realize a lot of experiments and a lot of, imagination about how photons or light can work. But the true level is much deeper than that picture.

1:09:53 TB: Yeah, I think, it's interesting, somebody in one of his lectures I think it was the New Zealand lecture, somebody asked him and said, "Dr. Feynman, do you think that your QED theory is the final theory that shows everything?" And Feynman immediately says, "No!" The bluntness with which he says it is remarkable. He just says, "No, this is not. This is a calculation, essentially a trick — a mathematical calculation trick that shows that certain simple assumptions lead to an unusual and unexpected level of calculational power.

But he had no illusions about it being the final answer to how some of this works. And, in fact, he was frustrated. There are interesting quotes. He always wanted to explain things to his dad. And he felt genuinely disappointed in himself. that he was never able to fully explain what an electron is to his dad. He was disappointed that he was never able to explain the self-energy of an electron.

So Feynman was keenly aware that his theory was not complete. The reason — what I like most about it — though, again, I may have a bit of a personal bias in this. He stuck to the old, old concept that in simplicity lies calculational power. And I think he proved that pretty darn well. He said that if we do nothing more than this, look at how precisely I can calculate certain properties of the electron. Now, does that mean it calculates the whole universe? No. I'd say there are huge things missing. Quantum field theory. Does it predict the entire universe? Good heavens, no, because it predicts that the universe will explode or collapse in an instant. So, if your theory… Predicts, which most quantum field theories do. that the entire universe is going to explode in an instant, you know, something needs to be done there. You know, you can't just add an arbitrary constant, which is what they do right now for it, and say, yeah, we'll just cancel that out. So… So, yeah, Feynman's theory was not a final theory. Quantum field theory is definitely not a final theory, because it only explains locally. Locally does extremely well. Across, cosmic spans of space, it does not do well. And, also, has difficulty, handling Just simple relationships of why the universe exists at all.

1:12:28 SZ: Yeah, but in that direction, in this philosophy, you can say that all theories are kinds of approximations that do not describe everything.

1:12:39 TB: Well, and that certainly was one of Feynman's adamant theses. that's what shows up in his answers, is when people would ask him about his own theory, he'd say no. Now, unfortunately, I think too often, this is so tempting for every person in the world, I mean, whether in physics or not. is we all tend to want to say that whatever I have as a premise. that's the right premise. And then you start building everything around that premise. And Feynman did that. I mean, he said about particles. But he did it in a fashion in which you say, yeah, let's see if it actually works. And he got his to work a lot better even than probably he expected himself.

But if you… you insist that whatever your premise is, is going to be the idea that explains everything, you're probably in trouble right there, because always, always, always, we have to go back to experimental observation. So you look at some of the supersymmetry theories.

As an example, I always can't help but bring up. Supersymmetry would explain a lot of things. There's just one problem. We've had decades, decades of work That have shown not a single trace of supersymmetry being actually how the universe works. So, you can always use that excuse and say, well, we just have to try harder. *Or*, you can acknowledge that probably that idea is not how it works. And then go on and look at something else. Sometimes we get too entrenched in whatever idea we think is, that's gotta be it, that's gotta be it, that's the only way it can work. And, we want to be careful about that.

1:14:12 JJ: Terry, can you do a presentation on time crystals? I know Sebastian and Cube Poland has done some interesting work in this area, but for people who are not physicists and scientists at that level, it would be great to have a presentation how you're presenting things, which is a little clearer for the non-expert, so to say.

1:14:31 TB: That is a possibility for a future thing. I would have an initial reluctance to it because one thing I liked about doing Feynman is I have no problem being fully in sync with what's going on. I'm not sure I'm in sync with some of the interpretations of time crystals. Anytime someone talks about a time crystal that's driven by energy, I'm saying, like, "That's not a time crystal." But, yeah, that could be a possibility, but I would have to give some… I would definitely have to give some different viewpoints. To me, the time crystal is when there's no energy input. There's no energy input, yeah, sure. I mean, even here, I've just been talking about blurring time for 2 nanoseconds just using photons.

So, I would tend to lean to the idea that time crystals are probably more common than we think, but they're not quite what we think. And that some of the work here is interesting work, but… but it… calling it a time crystal, I'm not the only one who's questioned that. Calling it a time crystal, *if it's being driven*, is maybe not, ideal.

There is a, a YouTube physicist [Ben Miles], and I'm sorry I forget his name at the moment, but he has done A couple of excellent presentations on, time crystals. And my apologies, I don't recall who he is of that, but there are some YouTube resources for that also. But we'll keep that in mind as a possible future talk.

Other questions?

1:15:56 CP: Can I ask something? As a non-physicist, I just wonder if physics, unlike some other subjects, like engineering. Business appears to be more instrumental than ontology. instrument in terms of developing equations and so on, the mathematical… Descriptions, rather than… your ontology. I just wonder, for instance, in this case of work by Professor Richard Feynman, if this work on the quantum electrodynamics had some impractical… Applications in real engineering. Oh, it's just purity. Theoretical, descriptions, rather than engineering applications, so that's… that's… I wonder if you have had any understanding of Applications of his work on the quantum electrodynamics.

1:16:60 TB: Quantum electrodynamics, I've never actually looked at where and how it might have impacted specific areas. It has certainly helped on the theory side in terms of understanding particles, which of course was his goal in the first place. It also provides a… A basis for organizing the math and getting The math that is most definitely used, quite commonly, for any kind of optical phenomena. If you're trying to do optical computing, these issues are extremely relevant. If you're doing optical quantum computing, you would need to address some of these issues with that. And not sure if I can think of… specific examples… that's something, actually, I'll try to look at in that. He's had other issues where he's, brought up points, I remember he predicted quantum vortices. That are, He was just kind of casually looking at some other work, said, aren't you gonna get… aren't you gonna get vortex-like structures in this? And it turned out he was exactly right. I mean, under… under another set of circumstances, he could have got a Nobel Prize just for that prediction. But, While Feynman was very interested in the everyday world, he recognized his work in QED as being more of trying to understand the how the electrons work, and I don't think he put a really big emphasis on on would that lead to a new technology? I would say that it can, if you look at areas like quantum computing, that closer examination of some of Feynman's principles are still relevant for some issues of quantum computing. The current models that are used for quantum computing are more… on the Deutsch mini-world side, and I, as I mentioned before, Feynman was very much on the particle side. But with very interesting twists that no one had done before. And, I would still think that his work is relevant for analyzing quantum computing issues. The Deutsch model to be blunt about it, has not panned out well. It's been in play for decades, and People keep talking about error correction, but really what they're talking about is the fundamental limit Of how much information you can get out of one photon. One photon can only carry a very small amount of information, so you can talk about it interacting with an infinite number of worlds, but if you need an infinite number of photons to see those infinite number of worlds, what did you gain? And this is the problem that's the deeper problem that's going to a lot of qubit strategies. So, I think there would be interesting applications of it in… focused application of Feynman-type concepts on optical quantum computing.

1:19:52 CP: Thanks, thank you. Yeah, it's because I was thinking, but, well, I was trying to relate it with the when you talk about reflections of light, and I was thinking about refraction as well. Because more recently, over the past few years, there's been some development with metamaterials, with negative refraction. So, people have been developing this kind of technology for… for clocking, invisibility. Making things invisible. So, playing with lights, I was wondering whether the work of Hyman had any application in this kind of… status of this new, metamaterials, yeah. Thank you for your answer.

1:20:42 TB: I don't think Feynman worked directly with metamaterials, but he did work with negative probabilities, and had both scurrilous remarks, scurrilous things to say about them, but also very interested in them. And that's a domain of quantum mechanics where you get into this ambiguity about space and time.

Bill, you had a question? Bill?

1:21:03 WS: Yes, I just had to turn my audio on. I watched a video. early this morning. I was so excited about this lecture, I got up in the middle of the night. And I was just like, Feynman, Feynman, Feynman, I couldn't quit thinking about it. And I found this video on YouTube, that talked about when Wheeler, who was… Feynman's advisor. I got him to organize a presentation at Princeton And, two of the people that showed up, two of the most famous people that showed up. or Einstein and Pauli, And what… what Feynman was lecturing about was the characteristics of electrons… And how they… Oh… arm… the observability Of what happens when, they, they recoil. Yes. And so… arm… I… he had worked out the map, and it was all elegant, and I found out there was a subtle thing dropped into the description. That said that one of the things that they always wanted to avoid was, when the math leads to going to infinity, because it just kind of blows up. So… so he had… It had worked out the math. And, and delivered a very elegant lecture. Now, in his… in his biography, surely you're joking, Mr. Feynman, He lamented that he appreciated Einstein's reaction, but he wished that he had tuned in. He said it was such heavy stuff, like lecturing Einstein. that… that… it was like he wasn't all there in the room. He was freaking out. And so, matter of fact, to set the stage, Einstein walked up to him. And introduced himself just like he was a normal person at the very beginning. So, that was very disarming for Feynman. He loved it. But at the… at the end of the lecture, Polly, who is known to be kind of an irascible jerk. I said, well, this is all just a bunch of baloney, you don't know what you're talking about.

1:23:30 TB: That is so Paulie, yes.

1:23:34 WS: Yes. And so, Polly turns to Einstein, who's sitting next to him, and says, Albert, don't you agree? And, and So I… Dr. Einstein sat there for a second, and he goes, no! I don't agree, I don't agree. think, Dr. Feynman has, has, his ideas have some merit here. We need to explore this more. And… and so I, I, I invite people to go look for this, presentation to Einstein, you'll learn a lot about physics and the hierarchy of what's accepted and what's not. It's very political when it gets to the top.

1:24:18 TB: Pauli absolutely could be a jerk.

1:24:21 WS: And the example I point to is.

1:24:24 TB: The first time someone came to him with the idea of electron spin, to Pauli — which Pauli later got a Nobel Prize for! — he browbeat the man so severely that the man backed off from it and refused to accept it, even after Pauly switched. He actually essentially just brutalized the guy to the point where he no longer believed his own thoughts, and that guy was the one who should have gotten the Nobel Prize. Instead, Pauly got it! So, Paulie's not one of my favorite people now, and that's an example of why I think that was just so… But it's also who Polly was. His reaction was always to react as negatively as possible on the initial thing, and then he would consider it later. The trouble was that some people couldn't handle that. And in the case of the electron spin, the poor guy just… just couldn't… he couldn't accept it after that. Yeah, the ins… There's all sorts of interesting, stories of Feynman interacting with other physicists, especially early on. And Wheeler… one of my statements I like to make about Feynman is the… one of the greatest physicists, I won't say the greatest, but probably one of the greatest physicists of the last half of the 1900s was Wheeler-Feynman. Not Feynman, not Wheeler. Wheeler-Feynman, because when you put those two together. You put Wheeler, who just would go… Wheeler would just go out there, just explode everything, just come up with the craziest idea possible. And Feynman would sit there and say, no, no, hold on, hold on there, hold on, you know, let's tie that down a little bit. But the combination of those two, I think they were more powerful as a team than either of them was later. Feynman kind of settled into continuing to do his Feynman diagrams for other particles, which was good work, but also it was… it was more slugging along type stuff. Wheeler went out in some directions that are so wild that some… you read some of his stuff, and it's just like… But what do you… what do you even say? You know, it's really wild stuff. But Wheeler, for instance, he told Feynman He called up Feynman one day, and this is recorded in some of the books, and he says, Hey, hey, hey, Richard, Richard, I got an idea. There's only one electron in the universe. It goes forward in time as an electron, then backward in time as a positron, forward in time, and it does that an almost infinite number of times. And that's where the universe comes from. So, the universe is half antimatter and half matter. And Feynman… and Feynman looked at it, and his own comment says, like. Well, I couldn't agree with that idea, but I did like the kernel of it. Which was that electrons could go backwards in time. And he took it and developed the full period of QED, which I haven't gotten into those details. That's a fascinating part of it. Feynman really played games with time. He really did, and the positron is a good example. Feynman had that positive… that electron going backwards in time on short distances, so he took Wheeler's idea and took it in a more pragmatic direction. And the result was just beautiful, because that did produce an extremely predictive theory. But like I said, the combination of those two was marvelous. They had a respectful relationship with each other, they admired each other, but they had very different approaches. Just very different approaches.

1:27:47 WS: Sure. Terry, one other comment that I think people would find interesting. There was an American blues man by the name of Paul Pena, it was actually born on an island off the coast of Africa, but… Fascinating man. And he went with some Feynman fanatics. to… the country that has the center of Asia, it's called Tuva, or some people call it Tannu Tuva. And, the, the capital of Tannu Tuva is a place called Kyzyl. And, they're, they're, they're noted for having triangular stamps. And so, Feynman, who kind of considered himself an encyclopedia of everything, would bring it up in trivia discussions, saying, "Well, where is Kyzyl? And, what is the only country in the world that has triangular stamps?" So, with Ralph Layton, who was his protege and one of his best friends. they, they had planned a trip to Tuva.

And, it's all documented in the book *Tuva or Bust*. But… but what would happen was… are… between red tape. And… and the fact that… that they were under the… the control of the Soviet Union. He just couldn't get over there before he died. And, and so the, the mission… of Paul Pena, and, and, Ralph Layton's friends was to go over and, as a tribute to Feynman, go do this, and it turned out that Paul Pena was a genius. And he, through ham radio and shortwave radio, he had learned the Tuvan language and Russian. So, yeah, so he was able to go over there. In that area of the world, Mongolians and Tuvans can do something.

1:29:57 TB: And Tuva.

1:29:58 WS: Throat singing, exactly.

1:29:60 TB: I was thinking that the whole time, yes.

1:29:63 WS: Yes, and so I encourage people, if you really want to understand the final tribute to, Richard Feynman, go look at… Take a spoilers, because it's… it's imperfect, it's a documentary. But… Thank you. I mean, Paul Pena goes off his meds. I mean, he's going nuts over there in the last, the last one-fourth of the film, but it's unbelievable that he goes over there and, like, wins the World Series. You know, he gets a World Championship Award for throat singing, so… It's, it's the final tribute of, of, Richard Feynman to, you know, just go watch Vegas Blues and you'll get it.

1:30:60 TB: I'll definitely see that. I… the story about them planning that trip, I'm familiar with that story, I haven't seen that video, but that was so sad that Feynman died, he had two forms of cancer at once. He had been a little too cavalier at the nuclear tests, and he had exposed himself more than most people. Of course, the risks were not well known at the time of that, but it did have a cost to him. So, I mean, he lived until he was 69, but it definitely, he paid a toll for it. He paid a cost for it. But yeah, that was such a… They wanted to visit that place, and nowadays, tube and throat singing, for instance, you can find it on the internet, it's available, but it was such a marvelous and unusual thing, and… And it was such an interesting location, and it's so characteristic of Feynman that he wanted to see that. He wanted to go there, he wanted to experience that, he wanted to go with his friends. He's a very sociable person, and he wanted to, to see that, and of course, the sad thing is he did not. So, I'll be sure to watch that. Thank you. Other questions?

1:32:12 CP: Yes, quick comment there, Terry, about Richard Feynman. One comment about… he… he's… he was not only a physicist, he… great physicist. He was an accomplished musician. Yes. He was a very good Congress player. Yes, yes. And also, his work about the space shuttle. That failure of Space Charter was great.

1:32:36 TB: The space shuttle incident is incident… remember, as I mentioned, Feynman did not like he did not like people think they… that they had to respect… that they had to have respect. It doesn't mean he didn't respect people. I mean, Feynman had enormous respect. If there's anyone that Feynman idolized, it was Dirac. And Dirac was kind of completely indifferent to Feynman, which is just unusual. Because Feynman would try to talk to Dirac. Feynman was inspired by Dirac, Feynman got his key words.

1:32:65 CP: Yes, but Paul Dirac was autistic.

1:32:68 TB: But Dirac just seemed annoyed with Feynman! There's this one-line paragraph, that I'm pretty sure he's referring to Feynman, in which he grouses about people who have gone off into another direction, and not paying attention to the Hamiltonian. Dirac dove *totally* into the Hamiltonian, and disregarded the Lagrangian. And, apparently, this was a snipe at Feynman, one where Dirac was saying, you know, "Why are you *doing* that?"

But Feynman got the idea from Dirac! It was an obscure paper by Dirac that gave him the entire idea of following the Lagrangian! And then, for Dirac to just dismiss him?

Yes, Dirac is a fascinating person. An extremely difficult person to know — as you say, he was probably autistic. It was a hard-to-describe person. His intuitions were impeccable, but his analogies sometimes were strange, such as the whole thing about the electron sea. There are so many reasons why you would *never* get away with proposing that idea in a physics class outside of that.

And yet, even despite the strain, because you're filling space with charged particles with nothing else. And yet he captured the essence of semiconductors, much later, with that model, and was able to express the positrons in it also. So, Dirac's instincts and his ability to see things were just very difficult to explain, and fascinating, and fascinating.

And I'll put Einstein a little bit in that same category. Einstein was not a visual thinker. People think he's a visual thinker. That was Minkowski. Einstein was… kind of a human physics emulator? And then he, with difficulty, he would try to express what he saw when he emulated physics inside of his head. is the only way I've ever figured out to describe how Einstein did his thinking, because if you've never read an Einstein paper originally, it's really worth reading, because that man's mind is just amazing. Same for Dirac. You know, you just… you need to read… some of these people's original papers, not what people write about them. Read what they thought, read what they said, because when it was in their heads, it was different. It was not the same thing that developed after that, ever

So these original papers are always… Very insightful for understanding the range of thoughts I had to go through to come to some of these conclusions, and also quite baffling sometimes on how they actually came up with those final conclusions.

Einstein's papers have certain areas where he just has kind of a leap of faith, and you kind of go like, I don't really understand how he got from there to there — and that includes where he equals MC squared, by the way, which, for him was L; he never used E. He never used that equation in the paper, by the way. He used a different equation, and didn't actually set it up as an equation, even. But, he did get that characterization, but how he got there was a little mysterious.

So, early initial papers, they… reading them and trying to understand them is just so… I think enlightening about some of these just amazing minds. Other questions? We may be nearing an end here, then. Helen, are you there?

1:36:38 HM: Yes, yes, I'm here. Yeah, so, so far, I don't see any… questions. I see some comments that this is extremely good. This was interesting, and you have a way of keeping things light and serious simultaneously.

1:36:53 TB: Oh, okay.

1:36:55 HM: Yeah, I got a lot of good feedback, yeah.

1:36:58 TB: Well, thank you, everybody. I guess we can go ahead and wrap it up. Thank you, everybody, for attending. I don't know when, but I certainly want to complete this, because this is just the tip of the iceberg. I mean, some of the really fun stuff is when you start getting into the interactions of the electrons and photons, so I definitely do want to do that in the future and talk more about Feynman's, Feynman's thinking of these concepts.

So, thank you, everybody!

1:37:23 HM: Goodbye. See you next week.