An Easy Intro to Feynman's Quantum ElectroDynamics (QED)

Part 1: The Quantum Physics of Soap Bubbles

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Overview

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II. Photons: Particles of Light
III. The Mystery of Partial Reflection
IV. Feynman's Particle-Based Approach
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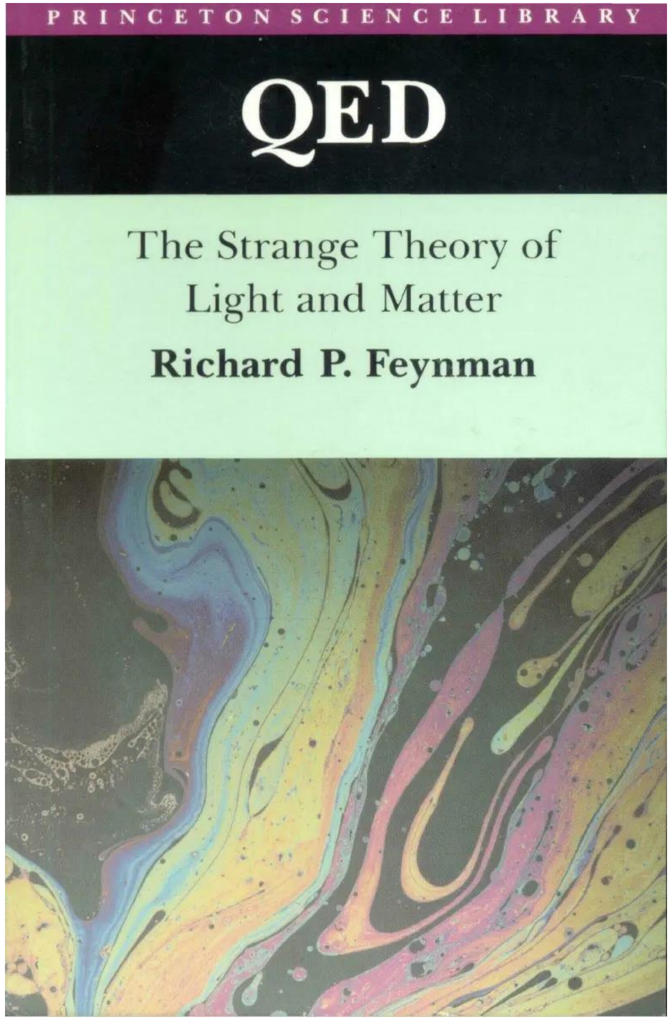
Part I.
Who Is Feynman and What Is QED?

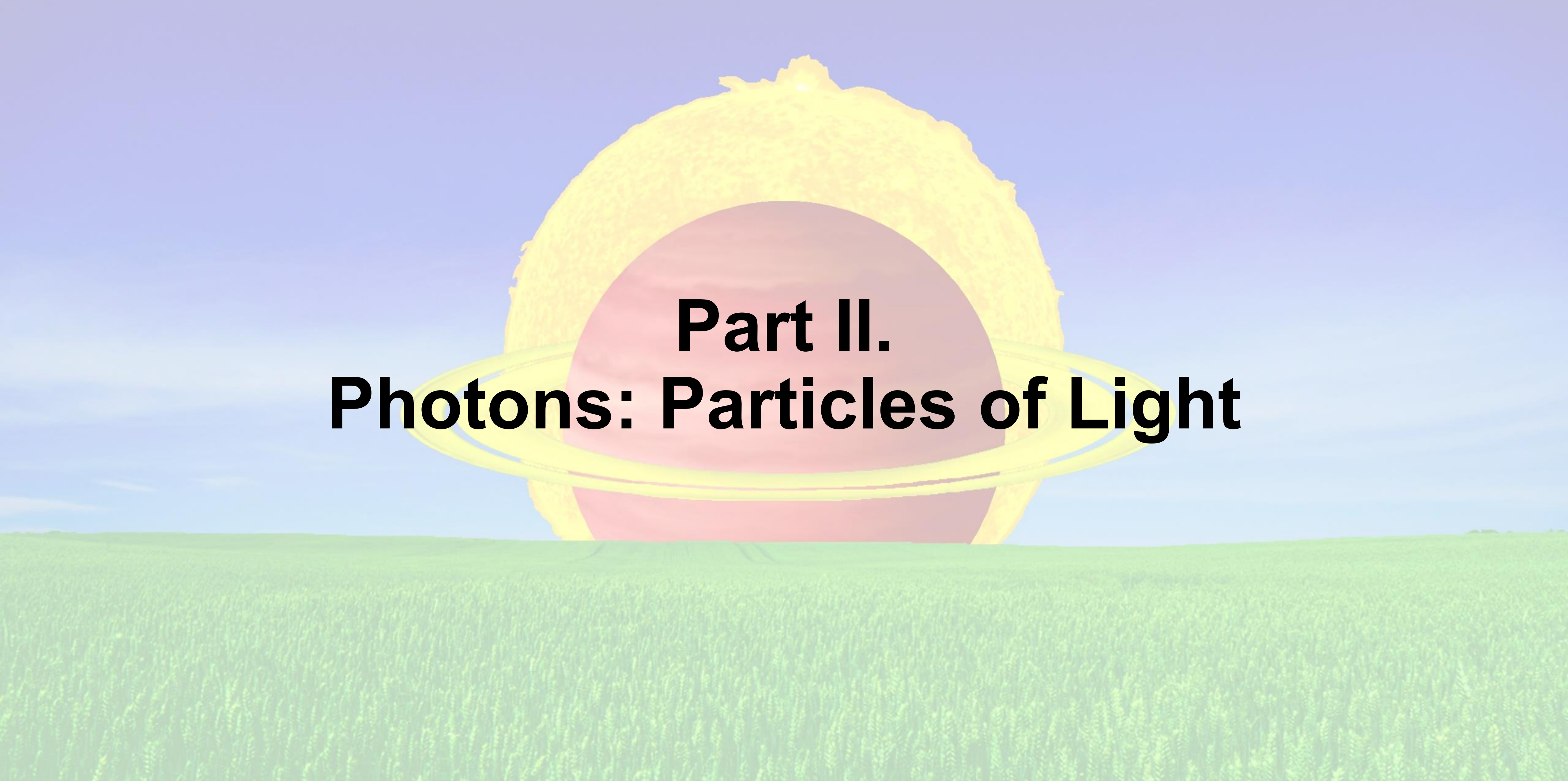
Who Was Richard Feynman?

- A notoriously bright and irreverent theoretical physicist of the mid-to-late 1900s. Born May 11, 1918, and died on February 15, 1988, at age 69. “Proper respect” was a foreign concept to Feynman.
- He was the author of several books popularizing physics:
  - Especially large, deep, and notable: *The Feynman Lectures on Physics* Available free online at: https://www.feynmanlectures.caltech.edu/
  - Notable books on Feynman’s irreverent approach include Ralph Leighton’s collections of anecdotes, *Surely You're Joking, Mr. Feynman!* (1985), and *What Do You Care What Other People Think?* (1988).
- His physics contributions included exceptionally precise methods for predicting electron properties (Quantum Electrodynamics, QED)

What Is QED?

- In physics, QED stands for Richard Feynman's theory of Quantum Electrodynamics
- QED is an example of a Quantum Field Theory — a theory of how fundamental particles interact at the deeper, non-classical level of quantum mechanics
- For QED, Feynman shared a 1965 Nobel Physics Prize with Julian Schwinger & Shin'ichirō Tomonaga
- QED is also the title of a Feynman book in which he explains his QED theory *without* using math (!!)
- Full book is at: https://archive.org/details/153980862-qed-the-strange-theory-of-light-and-matter-1/mode/1up?view=theater





Part II.
Photons: Particles of Light

One Way to Tell Light Is a Particle (a “Photon”)

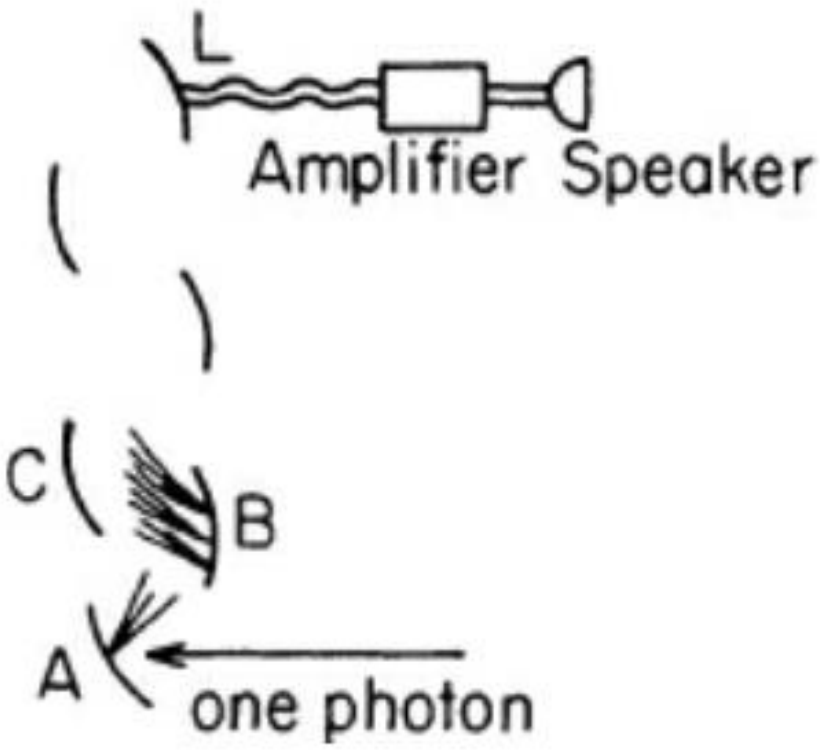


FIGURE 1. A photomultiplier can detect a single photon. When a photon strikes plate A, an electron is knocked loose and attracted to positively charged plate B, knocking more electrons loose. This process continues until billions of electrons strike the last plate, L, and produce an electric current, which is amplified by a regular amplifier. If a speaker is connected to the amplifier, clicks of uniform loudness are heard each time a photon of a given color hits plate A.

These Days You Can View Photon Flashes Directly

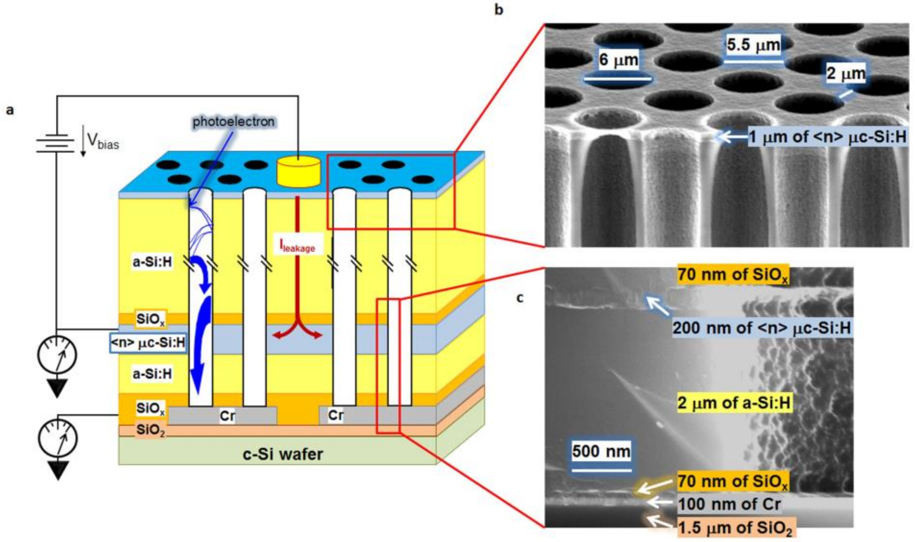
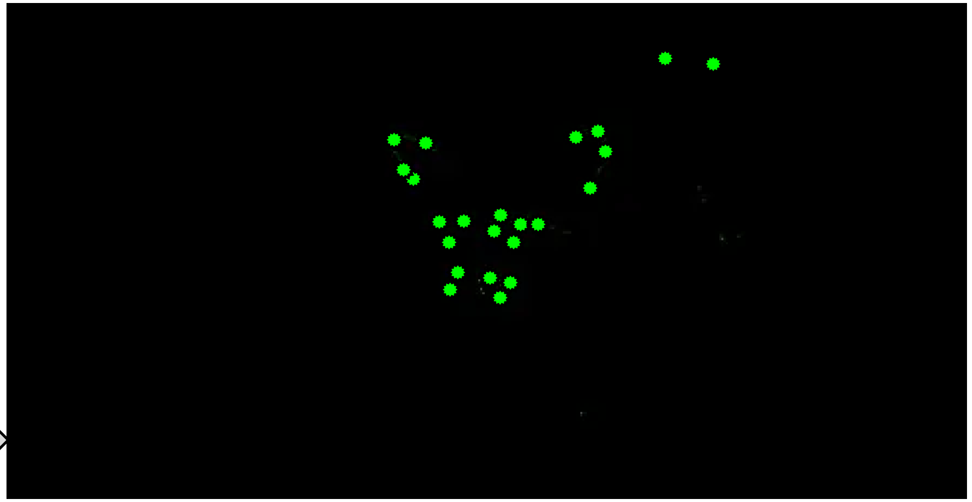


FIGURE 1-Extra. More recent light-amplifying technologies (e.g., “microchannel plates”) demonstrate how scenes in very dim light break down into individual photon-flash detections.

Very dim light

Almost no light



Einstein's One and Only Nobel Prize Was For…

… Figuring out that photons behave like particles. (Surprised?)

"… light [seems] better modeled by assuming that [its] energy … is not *spread continuously over ever larger volumes, but consists of a finite number of energy quanta that are spatially localized at points of space. [They] move without dividing, and are absorbed or generated only as whole [units]."*

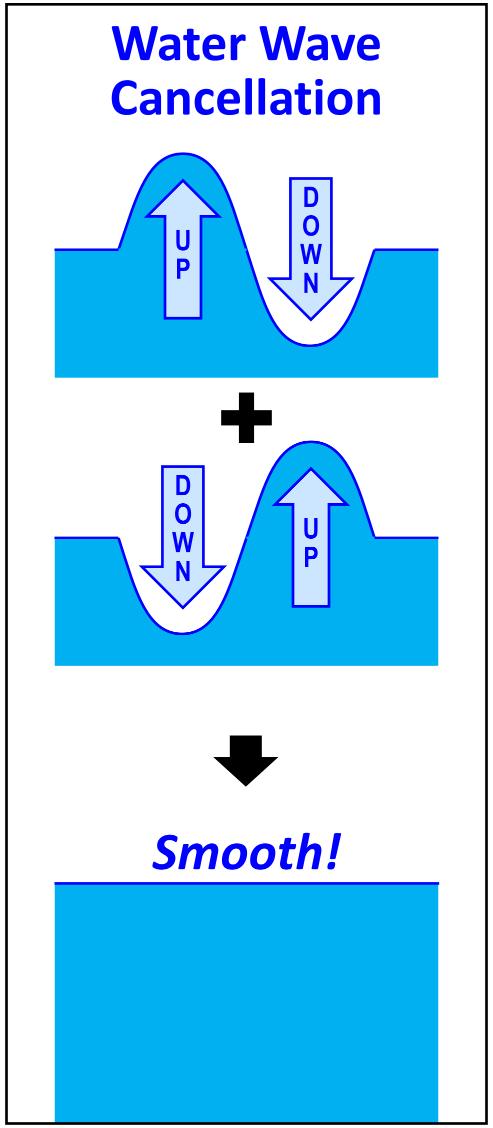
― A. Einstein, *On a Heuristic Point of View about the Creation and Conversion of Light*, Annalen der Physik **17** (1905). https://www.academia.edu/43729969/The_Scientific_Papers_Of_Albert_Einstein

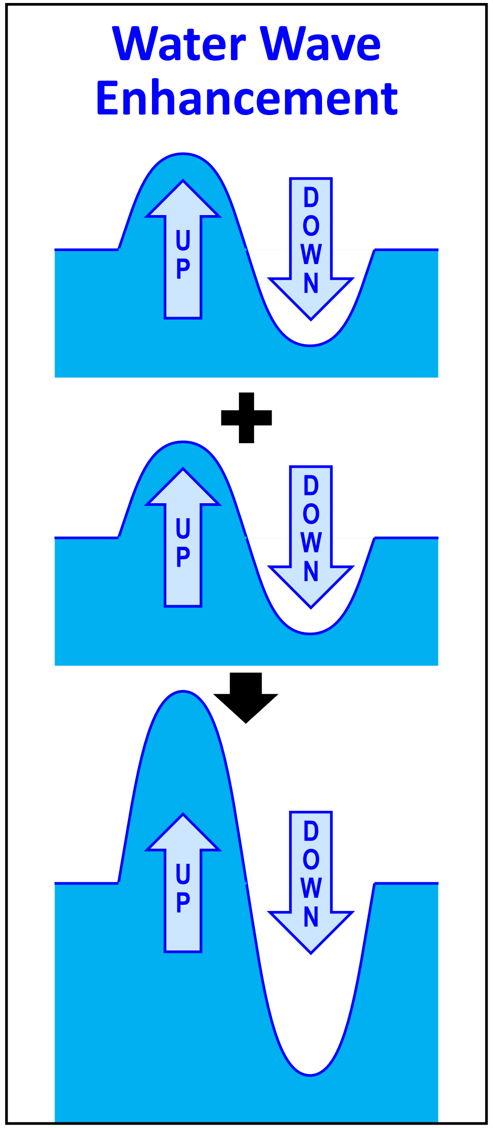
Einstein's 1905 perspective was Feynman's starting point

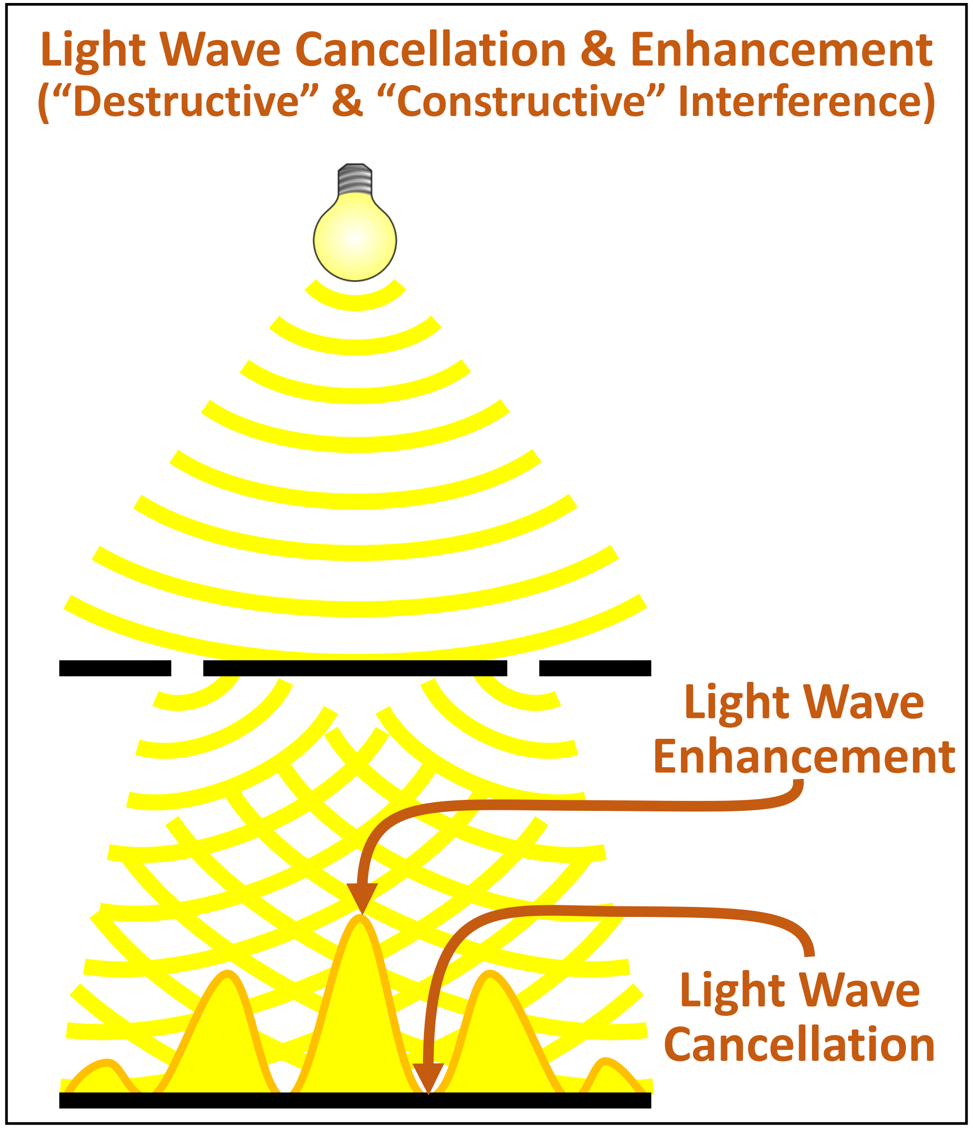
How Did Physicists React to Einstein's Idea?

- **Einstein's weird, upstart idea did not play well at all** (at first…)
- Physicists at that time knew the wave properties of light very well, and could not envision any reconciliation of wave light with photons
- Even when Einstein won the Nobel Prize for his paper on light corpuscles, the announcement did not mention his photon idea.
  - Instead, the announcement said he discovered the "photoelectric effect," in which light causes emission of electrons at precise energies
  - The view seems to have been that Einstein somehow "got the math right," but had used a model that made no physical sense
- Ironically, when physicists finally accepted the quantization of light, they gave most of the credit to Planck's earlier work on emission

The Concern: Centuries of Proof That Light Is a Wave







Addendum: Where Does the Cancelled Wave Energy Go?

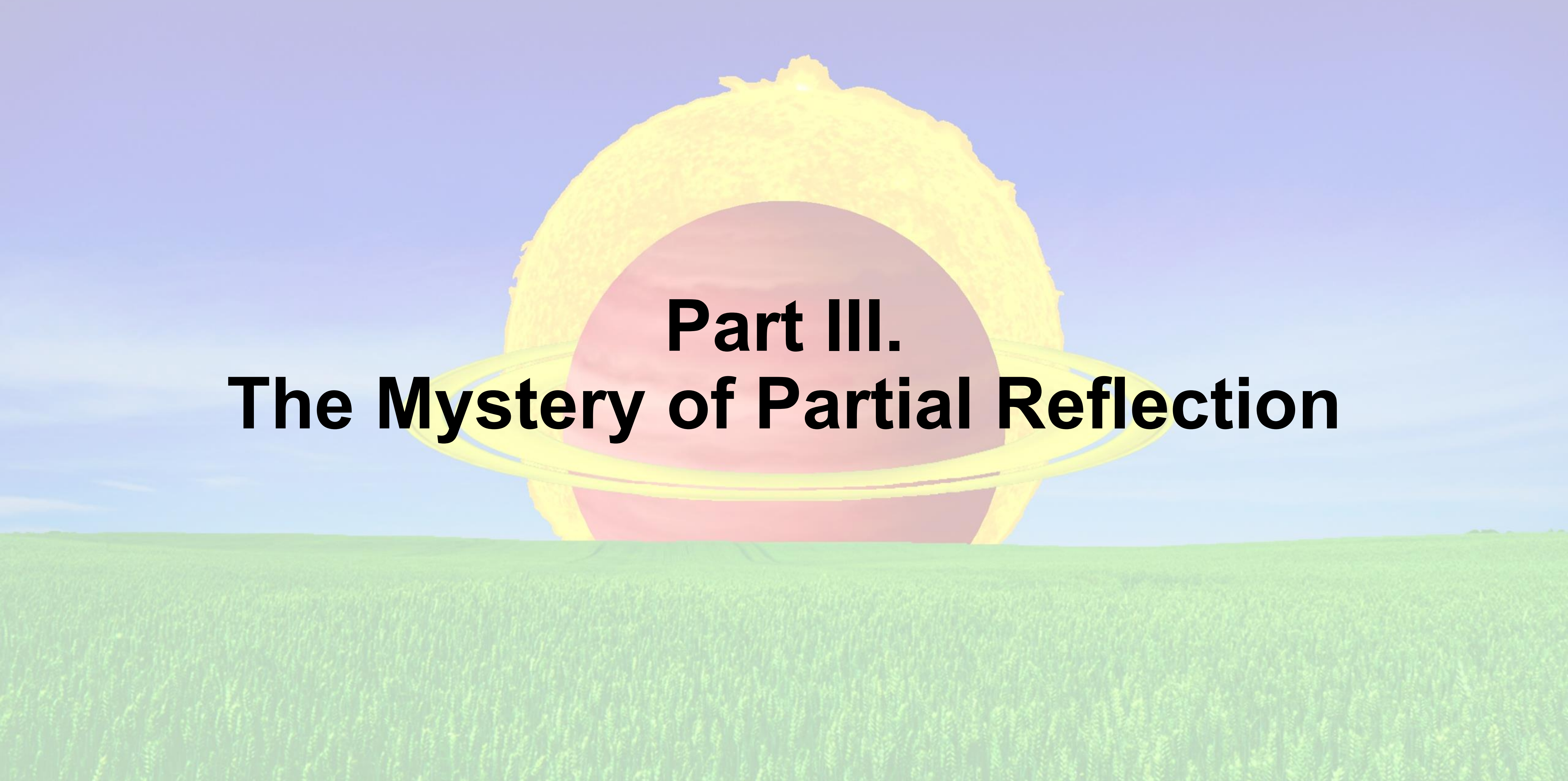
- Simple wave figures overlook the fact that waves always travel
- When you account for wave motion, cancellation becomes a region that forbids wave travel. Such regions are better known as mirrors:

> *"Keeping in mind the idea that waves always travel, here's what happens whenever you figure out a way to build a region in which the energy of such a moving wave cancels out fully: If you look closely, you will find that you have created a mirror, and that the missing energy has simply bounced off the region you created."*
>
> – https://physics.stackexchange.com/a/23953/7670, T.B., Apr 18, 2012

- In the photon model, they **forbid photons** from traveling in them (no "digging holes" or "making piles" in that region of space)

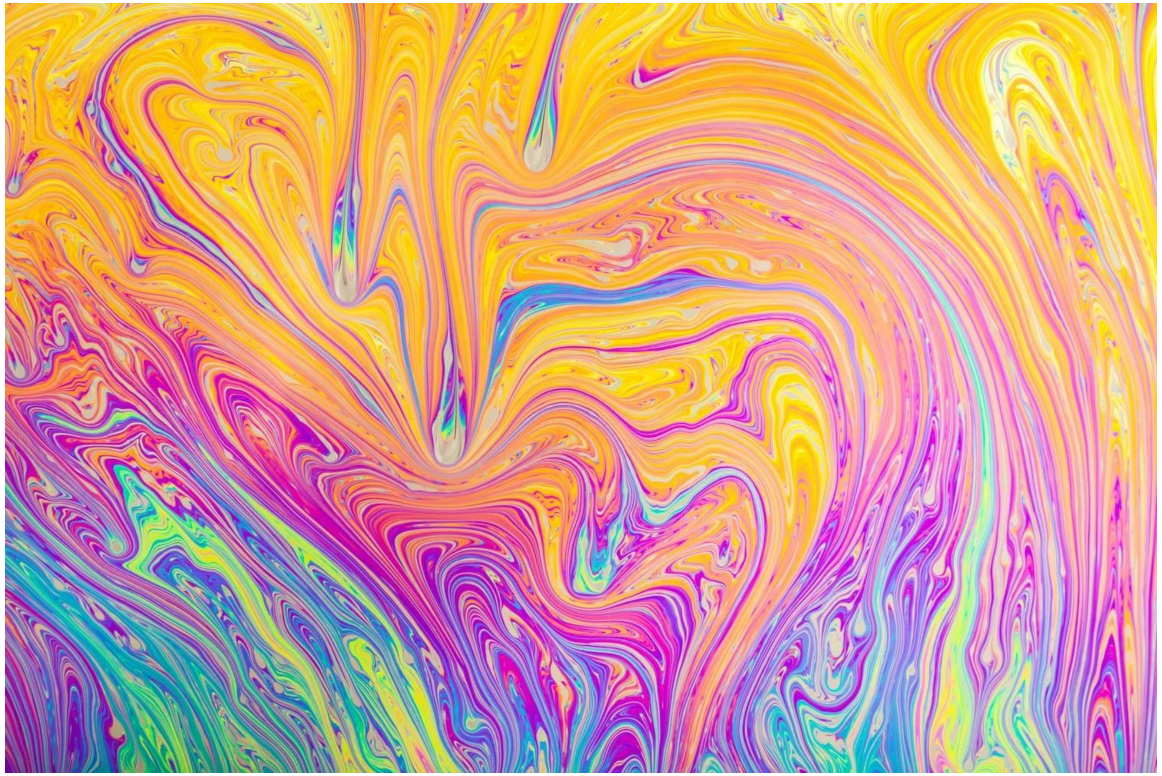
Feynman's Adamant Starting Point

- **Feynman chose to take Einstein's photons at face value**
- His goal was always to take the particle view, at every scale
- At the same time, Feynman took the wave behaviors of photons and other particles as absolutely beyond experimental doubt.
- Feynman also refused to add new "devices" (e.g., "pilot" waves)
- Instead, he sought to explain all wave-like behaviors in terms of a particles-only model with direct particle interactions (no fields!)
  - It is this goal of using only particles that drove his entire approach
  - His QED model worked better than even he expected for predicting values
- Feynman's particles-only approach also enabled a more intuitive approach to the complicated math needed to predict events



Part III.
The Mystery of Partial Reflection

Strange Light Reflections: Colored and Partial



Kym Cox: Colour Cascade No. 6 (2020 British Photography Award)
http://www.kymcox.com/about-1

Simple polished glass surfaces (lots of glare)

Specially coated glass surfaces (almost no glare)

Joe Wolfe, UNSW Physclips
https://www.animations.physics.unsw.edu.au/jw/light/non-reflective-coatings.html

Photons behave **very oddly** when **two reflective surfaces** are stacked close to each other and become equally available

The Centuries-Old Mystery of Partial Reflection

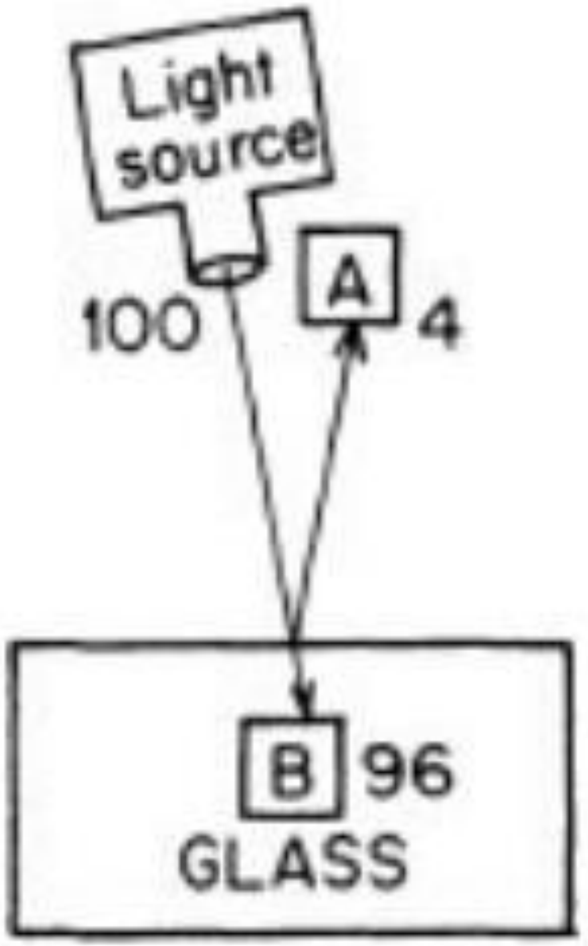


FIGURE 2. An experiment to measure the partial reflection of light by a single surface of glass. For every 100 photons that leave the light source, 4 are reflected by the front surface and end up in the photomultiplier at A, while the other 96 are transmitted by the front surface and end up in the photomultiplier at B.

One Theory: Partial Reflection Using Holes

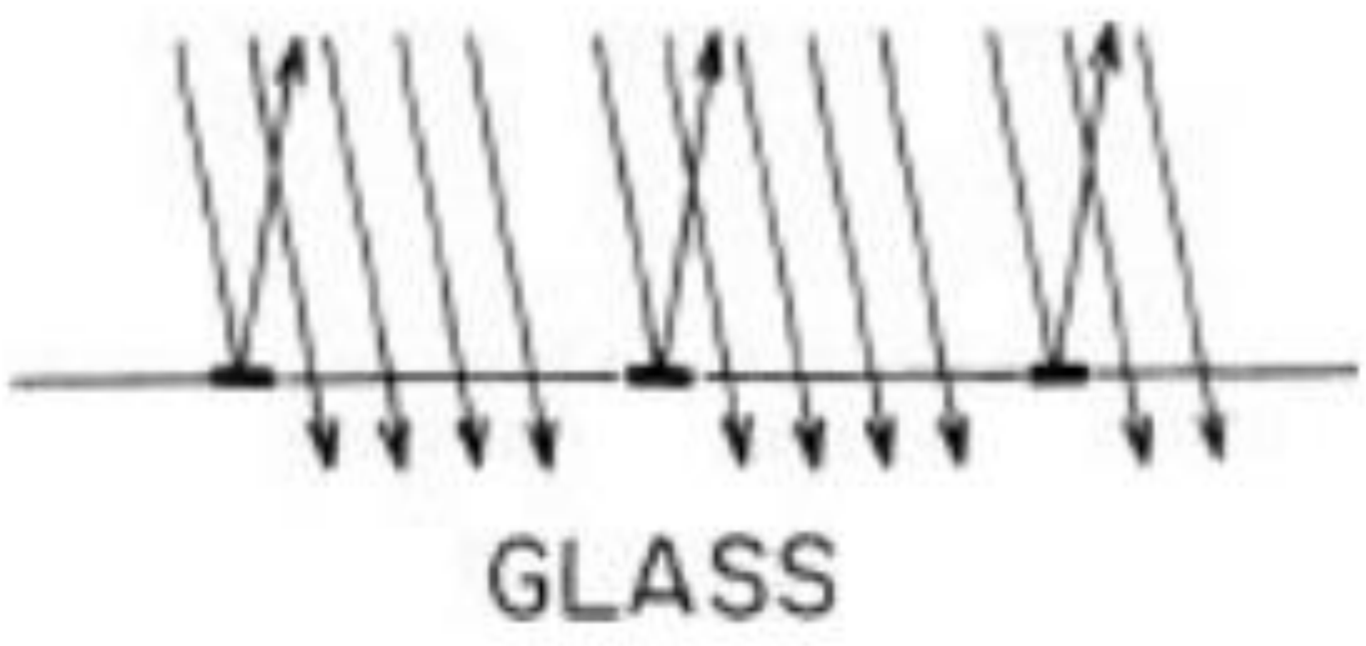


FIGURE 3. One theory to explain partial reflection by a single surface involves a surface made up mainly of “holes” that let light through, with a few “spots” that reflect the light.

Isaac Newton Was Mystified By Partial Reflection

- Isaac Newton believed light was particles (!) and had a question: *What, exactly, determines which photons reflect and which do not?*
- He was good with optical equipment and realized that:
  - The selection of photons could not be a surface-only effect
  - The number of reflected photons can vary widely, but predictably
- A remarkable point: *Newton was asking quantum mechanics questions centuries before quantum mechanics existed*
- To this day, we don't "really" know what determines photon paths
- Like Newton, we are still stuck with probabilities, not certainties

Part IV.
Feynman's Particle-Based Approach

Feynman's Photon Independence Assumption

- Feynman's photon independence assumption:

Every photon determines its own path

- That, when determining the final destination of the photons in a beam of light, it makes no difference whether the photons travel together (e.g., all photons in one intense laser pulse) or strung out over a potentially enormous time span (e.g., one photon per year)
- The value of this assumption is that if you can figure out the rules for how one photon travels, you have everything you need to know
- **This assumption has been rigorously validated experimentally**

One Photon Reflects from Multiple Locations

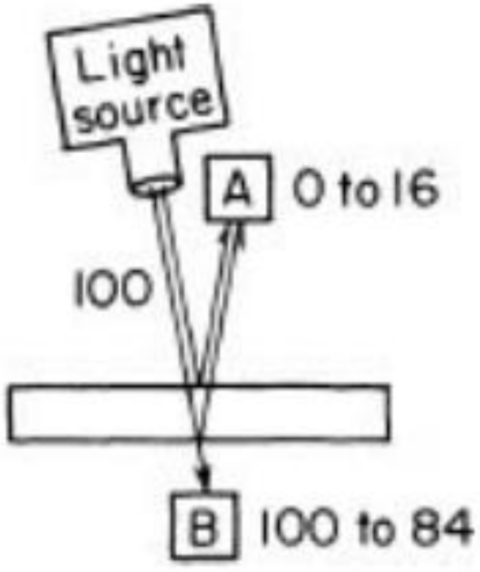
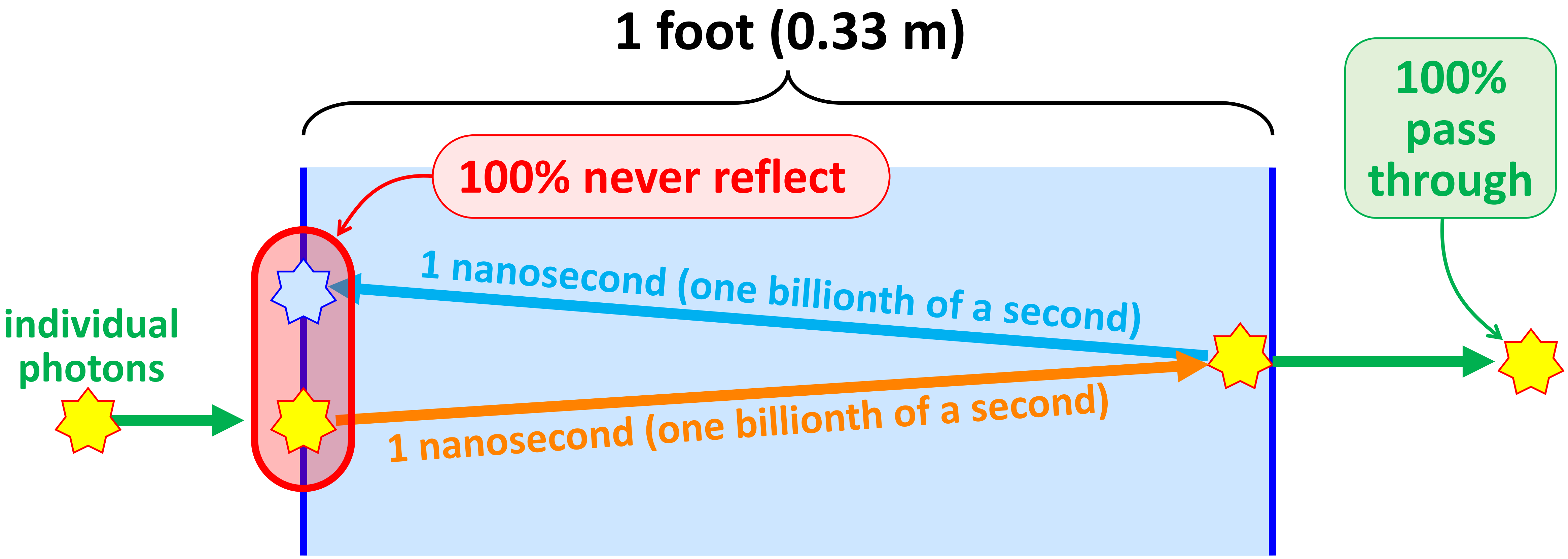


FIGURE 4. An experiment to measure the partial reflection of light by two surfaces of glass. Photons can get to the photomultiplier at A by reflecting off either the front surface or the back surface of the sheet of glass; alternatively, they could go through both surfaces and end up hitting the photomultiplier at B. Depending on the thickness of the glass, 0 to 16 photons out of every 100 get to the photomultiplier at A. These results pose difficulties for any reasonable theory, including the one in Figure 3. **It appears that partial reflection can be "turned off" or "amplified" by the presence of an additional surface.**

Ponder This: Your Eyeglasses Are Messing with Time

- Think for a moment about a photon being a single particle
- If it is a single particle, how can it reflect from two surfaces?
  - If two surfaces reflect one photon, it must “see” both of those surfaces
  - However, it arrives at those two surfaces at different times
  - With nothing more added, your no-glare glasses just played with time
- Feynman instead fully embraced this highly non-classical concept
- With Wheeler, he fully embraced photons moving backward in time
- Fully embracing standard quantum space and time uncertainty ended up making his math more precise and easier to specify

Foot-thick No-Glare "Loses" Photons for 2 ns in Time (!)



Two nanoseconds *after* the photon hits the glass front, its reflection from the far side of the glass cancels the existence of the reflection

Part V.
Using Experiments to Find Patterns

Reflection From Two Surfaces Is Bizarre!

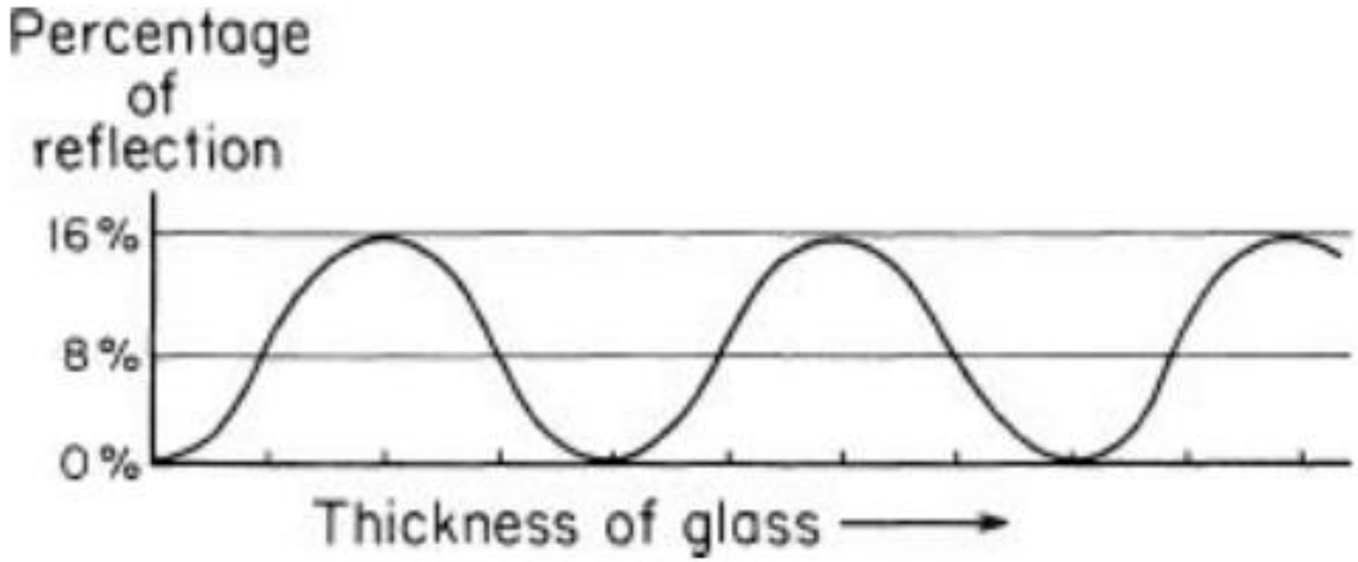


FIGURE 5. The results of an experiment carefully measuring the relationship between the thickness of a sheet of glass and partial reflection demonstrate a phenomenon called "interference." As the thickness of the glass increases, partial reflection goes through a repeating cycle of zero to 16%, with no signs of dying out.

Squaring an Arrow Length Gives Probability

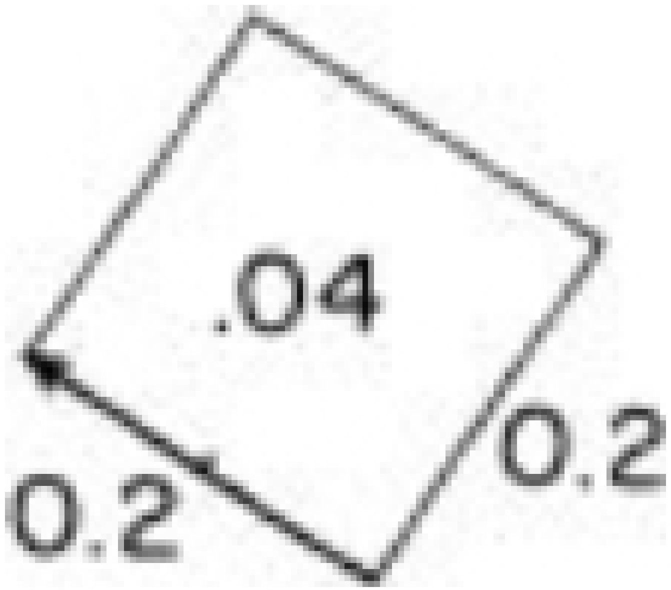


FIGURE 6. The strange feature of partial reflection by two surfaces has forced physicists away from making absolute predictions to merely calculating the probability of an event. Quantum electrodynamics provides a method for doing this — **drawing little arrows on a piece of paper. [☺]** The probability of an event is represented by **the area of the square on an arrow**. For example, an arrow representing a probability of 0.04 (4%) has a length of 0.2.

Figuring Out Arrow Lengths from Observed Data

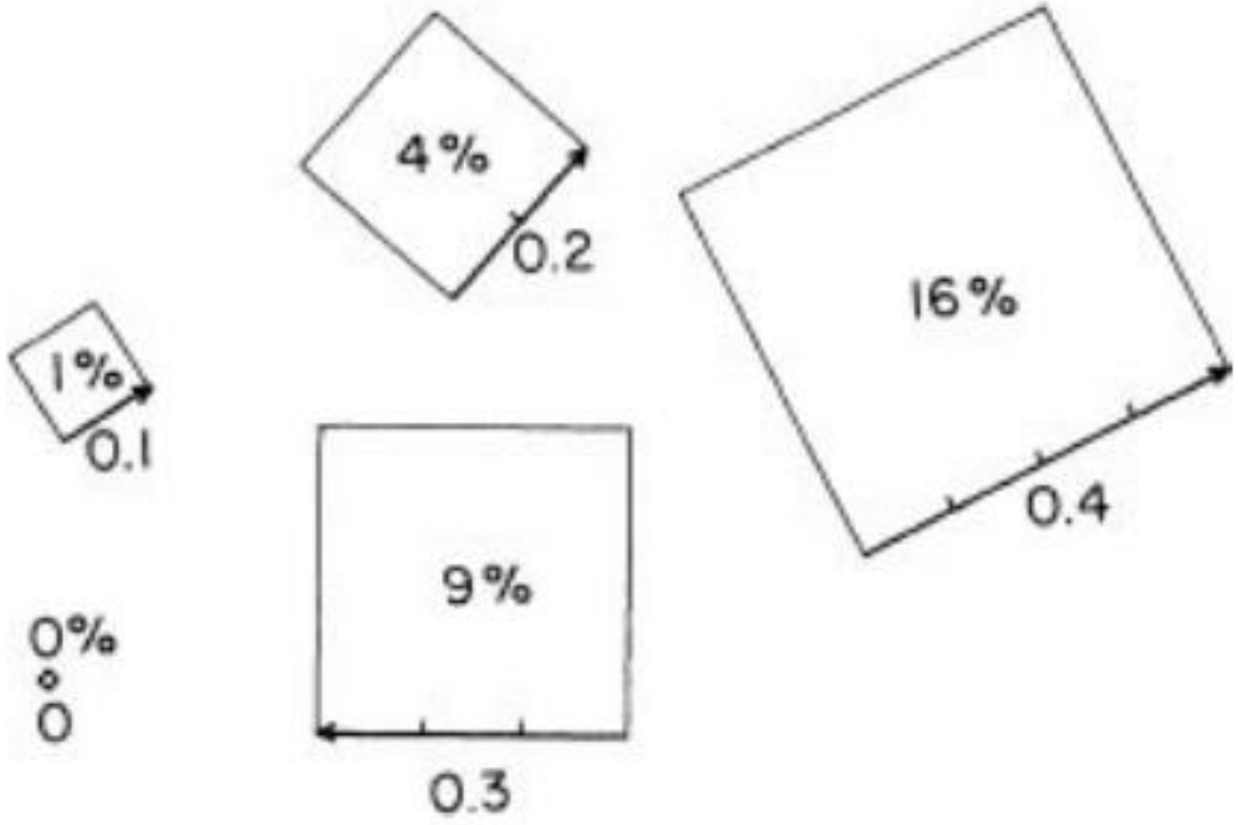


FIGURE 7. Arrows representing probabilities from 0% to 16% have lengths from 0 to 0.4. (A length of 1 represents 100% odds in favor.)

Adding Arrows by Placing Them Head to Tail

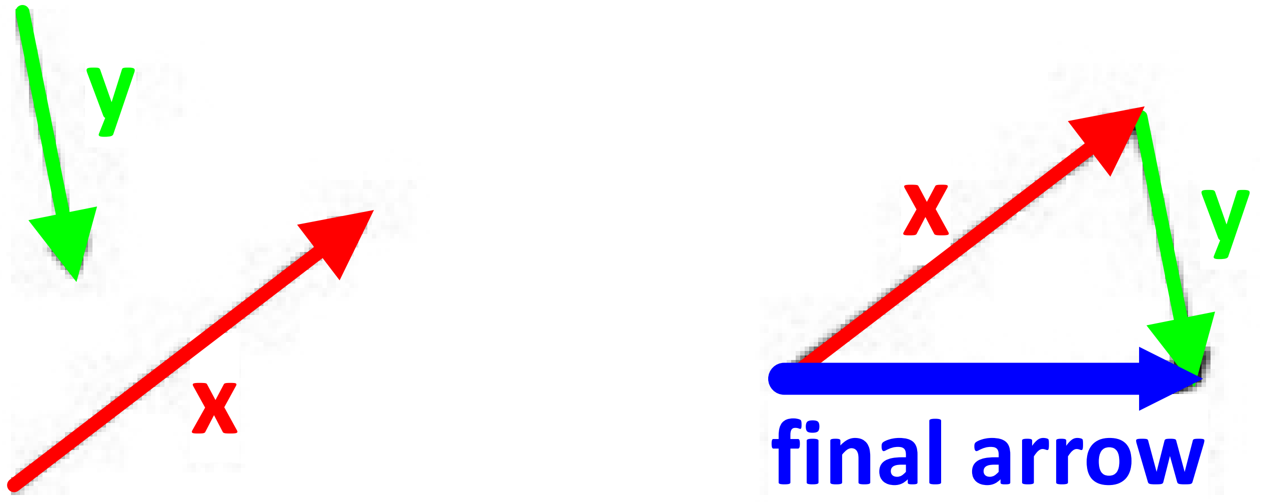
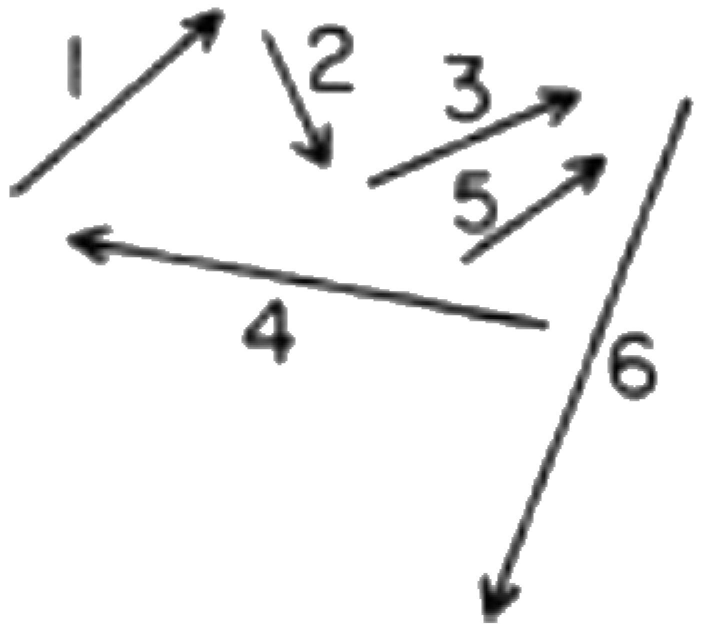


FIGURE 8. Arrows that represent each possible way an event could happen are drawn and then combined ("added") in the following manner: Attach the head of one arrow to the tail of another — without changing the direction of either one — and draw a "final arrow" from the tail of the first arrow to the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

You Can Add Any Number of Arrows by Chaining



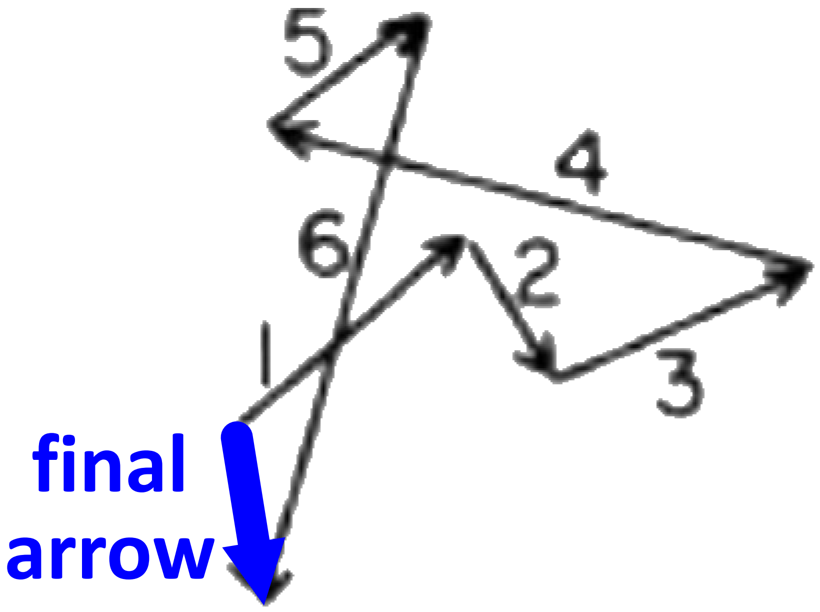
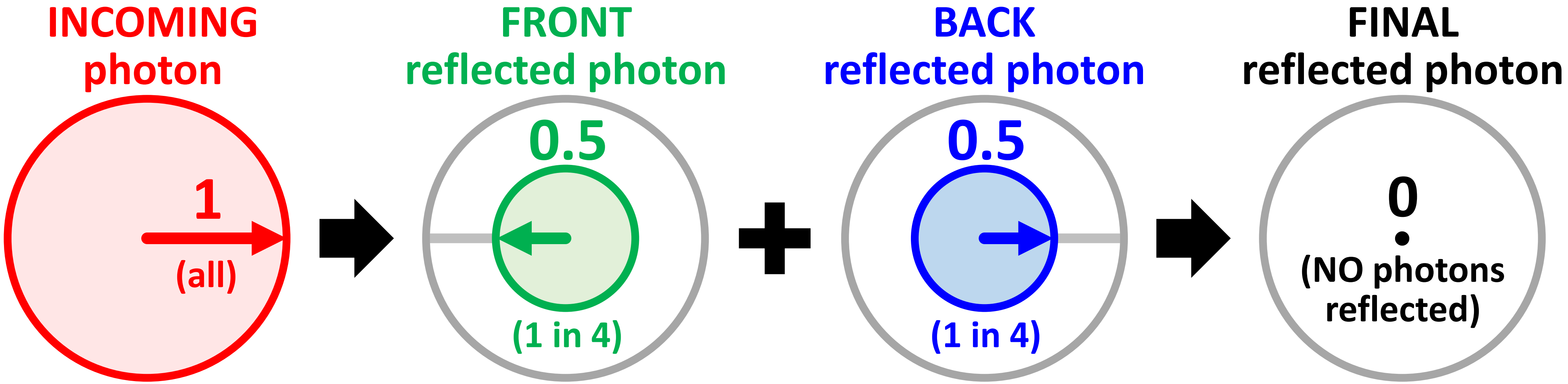


FIGURE 9. Any number of arrows can be added in the manner described in Figure 8.

Why Atomically Thin Films Are Transparent



"We need one more rule in order to compute the answer correctly: When we are considering the path of a photon bouncing off the *front* surface of the glass, we reverse the direction of the arrow. In other words, whereas we draw the *back* reflection arrow pointing in the *same* direction as the stopwatch hand, we draw the front reflection arrow in the *opposite* direction." *—Feynman, shortly after Figure 9*

Part VI. Stopwatches and Particle Reflections

Next Critical Math Step: Add a Stopwatch!

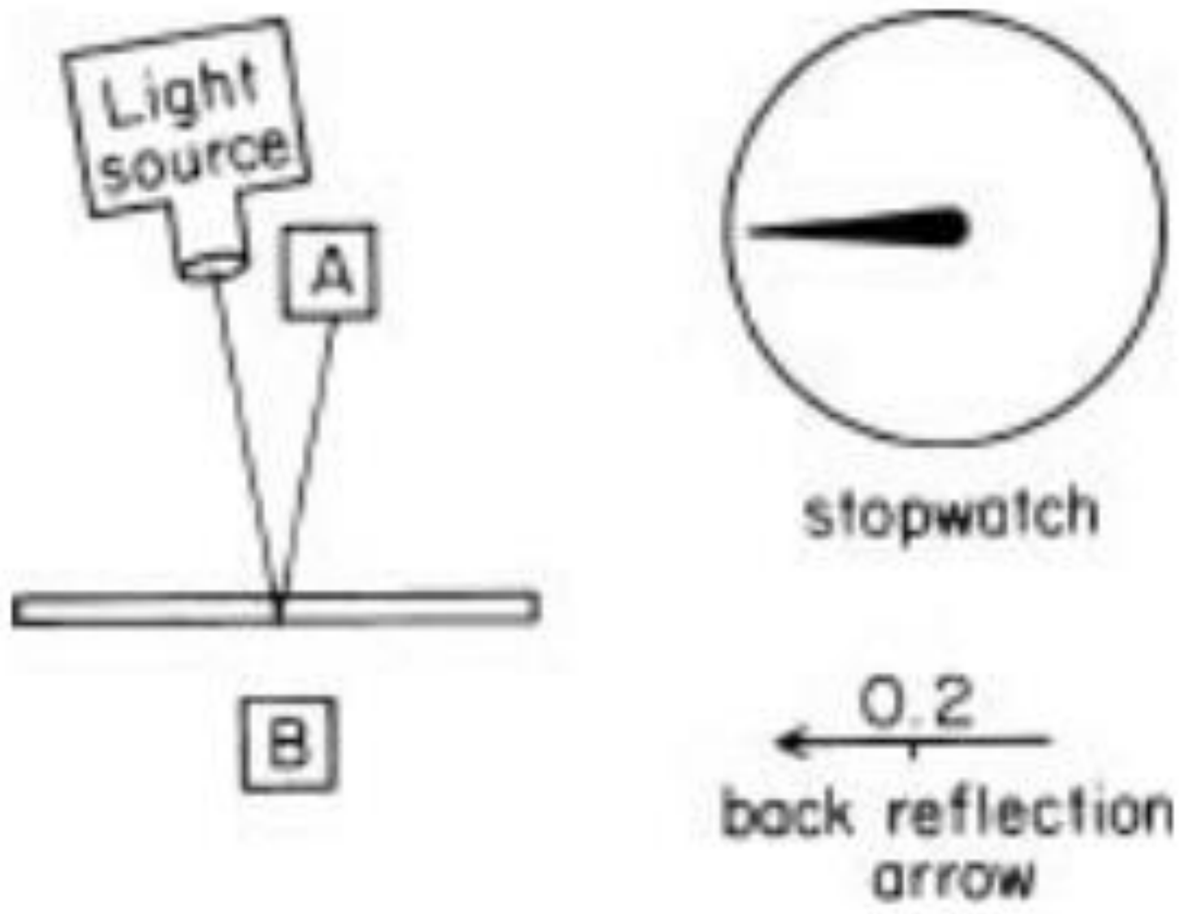


FIGURE 11. A photon bouncing off the back surface of a thin layer of glass takes slightly longer to get to A. Thus, the stopwatch hand ends up in a slightly different direction than it did when it timed the front reflection photon. The "back reflection" arrow is drawn in the same direction as the stopwatch hand.

Three Names for Feynman’s Stopwatch

“There are three different ways of measuring energy: by the [1] frequency of amplitude, by the [2] energy in the classical sense, or by the [3] mass measured by inertia. They’re all equivalent; they’re just different ways of saying the same thing.”

— Feynman in his April 29, 1963, Physics Lecture (audio). Edited book version: https://www\.feynmanlectures.caltech.edu/III_07.html#Ch7-S1-p6

- Feynman’s stopwatch is thus the total energy of the photon. It can speed up or slow down if you move toward or away from a photon.
  - The faster the stopwatch turns, the greater the total energy of the photon
  - “Matter” particles (e.g., electrons) have an intrinsic spin that motion cannot change. A matter particle’s minimum spin is better known as its rest mass.
  - Any time you see phrases such as “imaginary exponentials” in physics, these are just math ways of saying, “How fast is its stopwatch spinning?”

When the Time Change is Small, So is Reflection

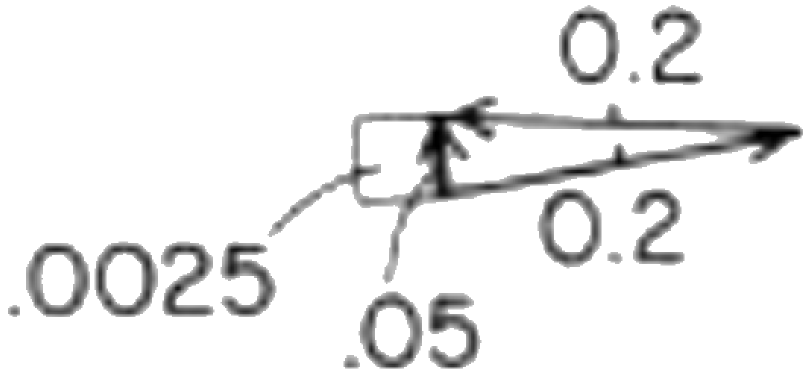


FIGURE 12. The final arrow, whose square represents the probability of reflection by an extremely thin layer of glass, is drawn by adding the front reflection arrow and the back reflection arrow. The result is nearly zero. [TB Note: Recall that the stopwatch arrow from the *front* reflection — the bottom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

Calculating the Final Reflection by Adding Arrows

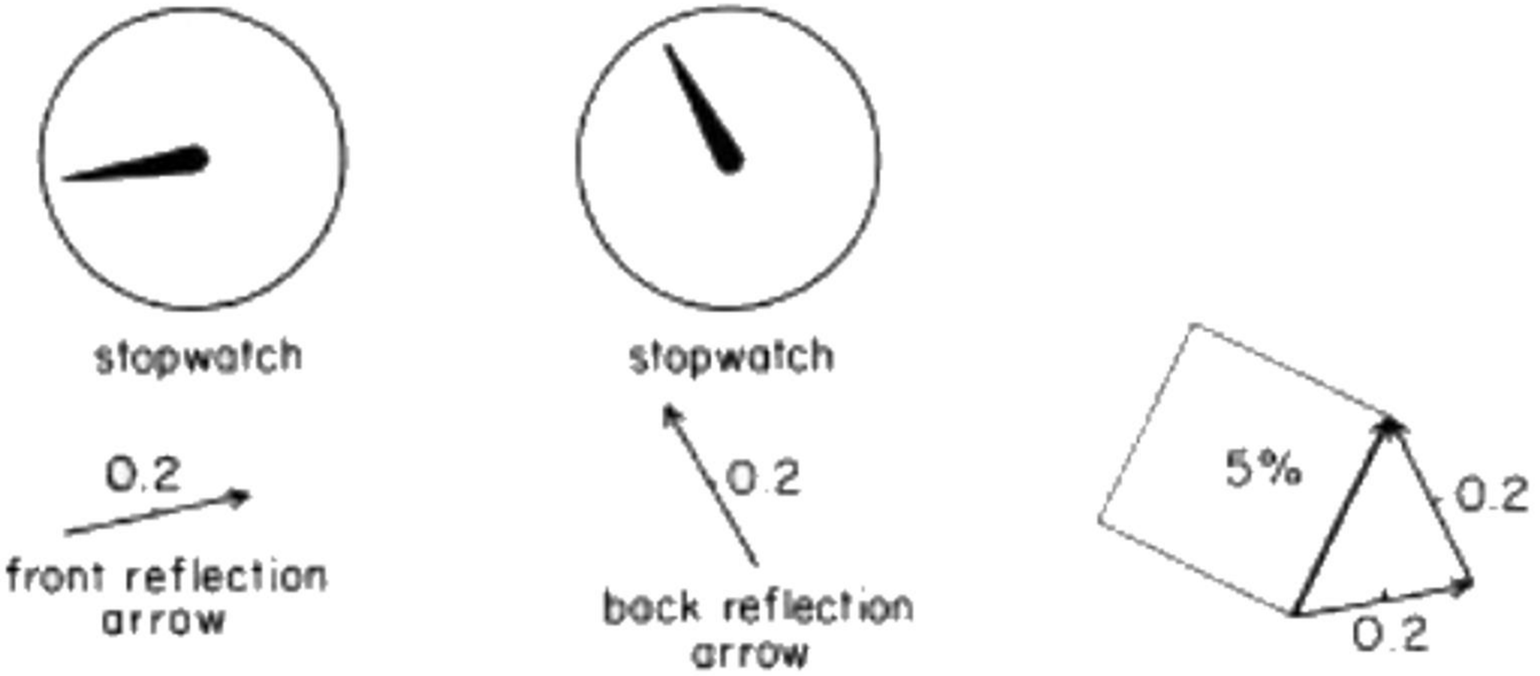


FIGURE 13. The final arrow for a slightly thicker sheet of glass is a little longer, due to the greater relative angle between the front and back reflection arrows. This is because a photon bouncing off the back surface takes a little longer to reach A compared to the previous example.

Maximum Reflection Occurs at Half-Turns

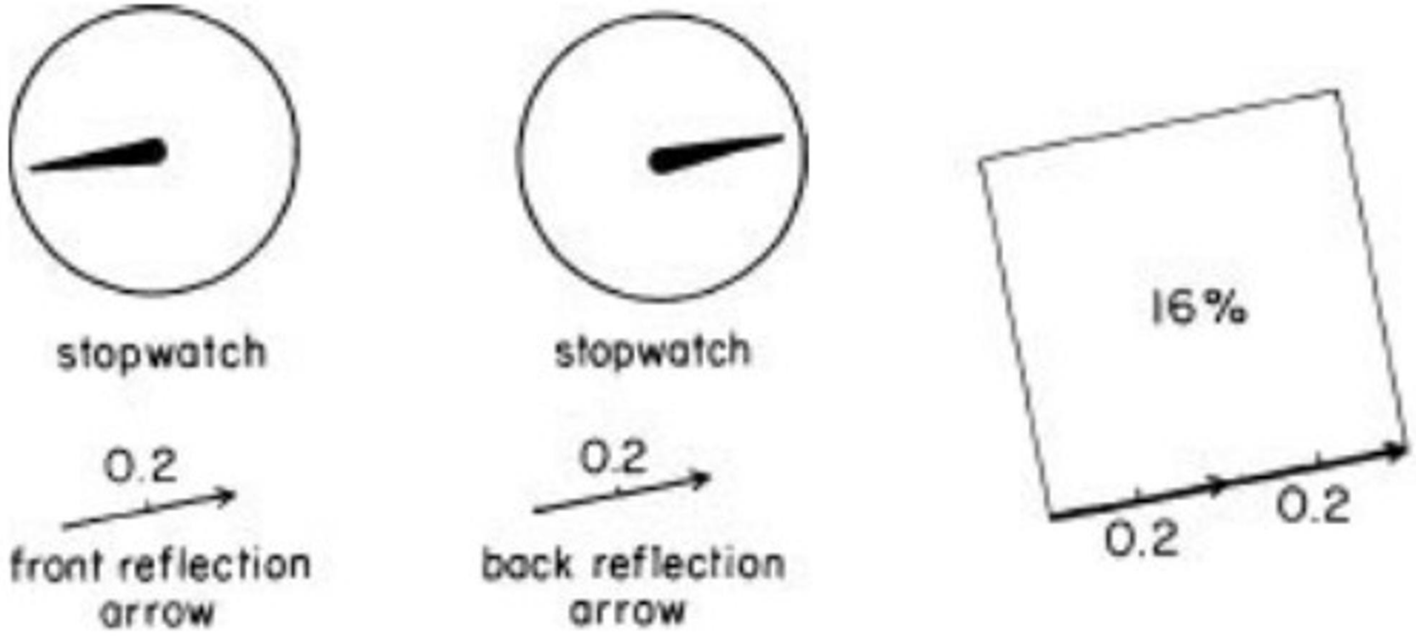


FIGURE 14. When the layer of glass is just thick enough to allow the stopwatch hand that is timing the back-reflecting photon to make an extra half turn, the front and back reflection arrows end up pointing in the same direction, resulting in a final arrow of length 0.4, which represents a probability of 16%.

You Can Also Cancel Reflection Completely

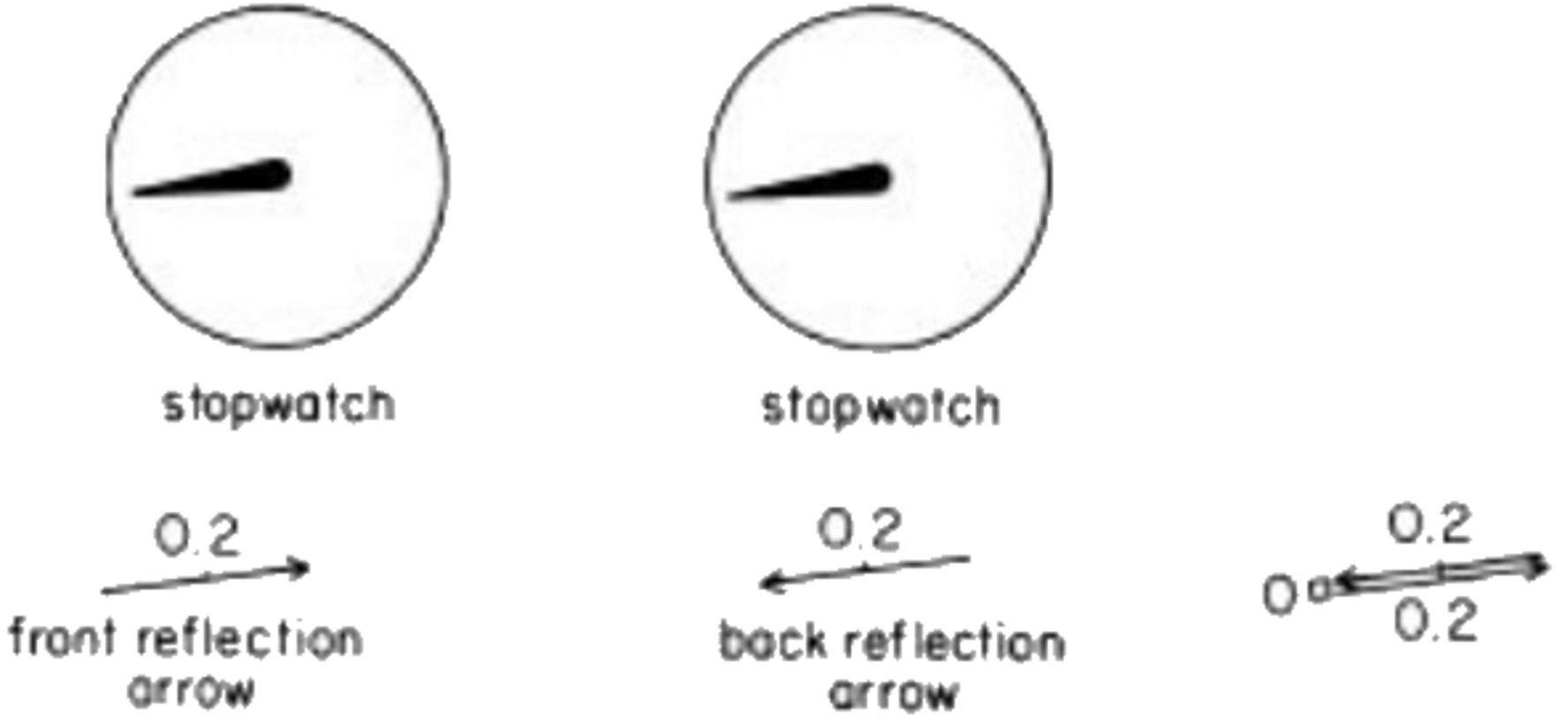


FIGURE 15. When the sheet of glass is just the right thickness to allow the stopwatch hand that is timing the back-reflecting photon to make one or more extra full turns, the final arrow is again zero, and there is no reflection at all.

Right Angles Give Pythagorean Sums of Squares

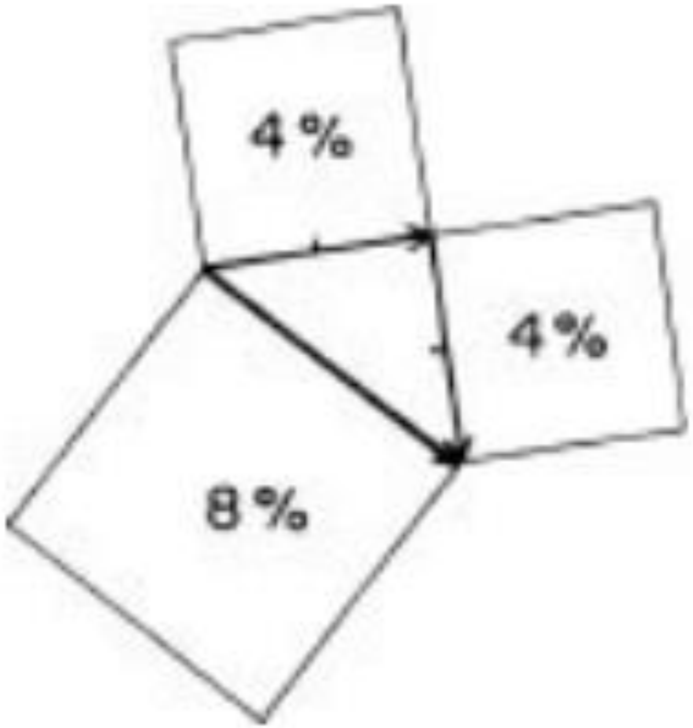


FIGURE 16. When the front and back reflection arrows are at right angles to each other, the final arrow is the hypotenuse of a right triangle. Thus, its square is the sum of the other two squares — 8%.

Part VII.
The Colors of Bubbles

Changing Arrow Angles Cause Repeating Cycles

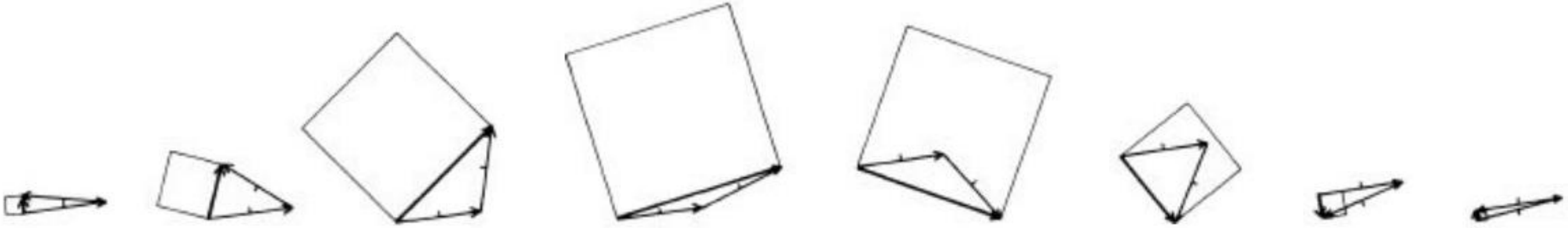
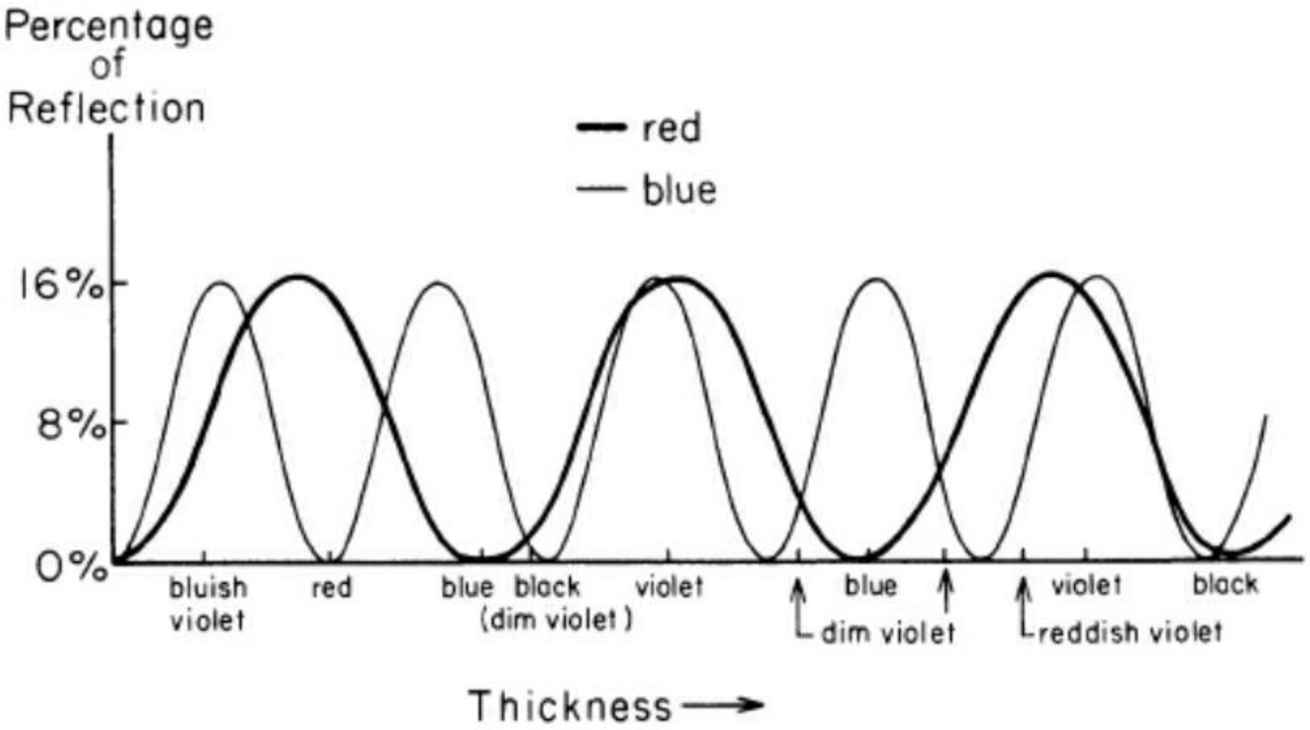


FIGURE 17. As thin sheets of glass are replaced by slightly thicker ones, the stopwatch hand timing a photon reflecting off the back surface turns slightly more, and the relative angle between the front and back reflection arrows changes. This causes the final arrow to change in length, and its square to change in size from 0% to 16% back to 0%, over and over.

Different Colors Photons Cancel at Different Widths



Wikimedia BDB, Aug 1, 2003, Traquair House, Scotland,

FIGURE 18. As the thickness of a layer increases, the two surfaces produce a partial reflection of monochromatic light whose probability fluctuates in a cycle from 0% to 16%. Since the speed of the imaginary stopwatch hand is different for different colors of light, the cycle repeats itself at different rates. Thus, when two colors, such as pure red and pure blue, are aimed at the layer, a given thickness will reflect only red, only blue, both red and blue in different proportions (which produce various hues of violet), or neither color (black). If the layer is of varying thicknesses, such as a drop of oil spreading out on a mud puddle, all of the combinations will occur. **In sunlight, which consists of all colors, all sorts of combinations occur, which produce lots of colors. [Pretty Soap Bubbles!]**

Part VIII.
Conclusion: Bubbles Reveal Deep Physics

Conclusion: Bubbles Reveal Deep Physics

- **Soap bubbles are pretty because they play games with time**
- Einstein was sure photons are particles (very few agreed at first)
- Feynman took Einstein more seriously than anyone, but…
  - Feynman also had to embrace the idea that a single photon can exist at more than one time and more than one location
  - These photon versions changed in strange but precise, wave-like ways
  - As we'll see, Feynman's **classical time and locations for particles emerged from large-scale sums of his many possible particle paths**
  - Feynman scoffed (quietly) at ideas like "pilot waves" to guide his photons because he needed nothing but particles (and a looser form of spacetime)
- Feynman's insights enabled new levels of calculation precision