An Easy Intro to Feynman's QED

Part 2: Adding Alternative Histories

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Overview

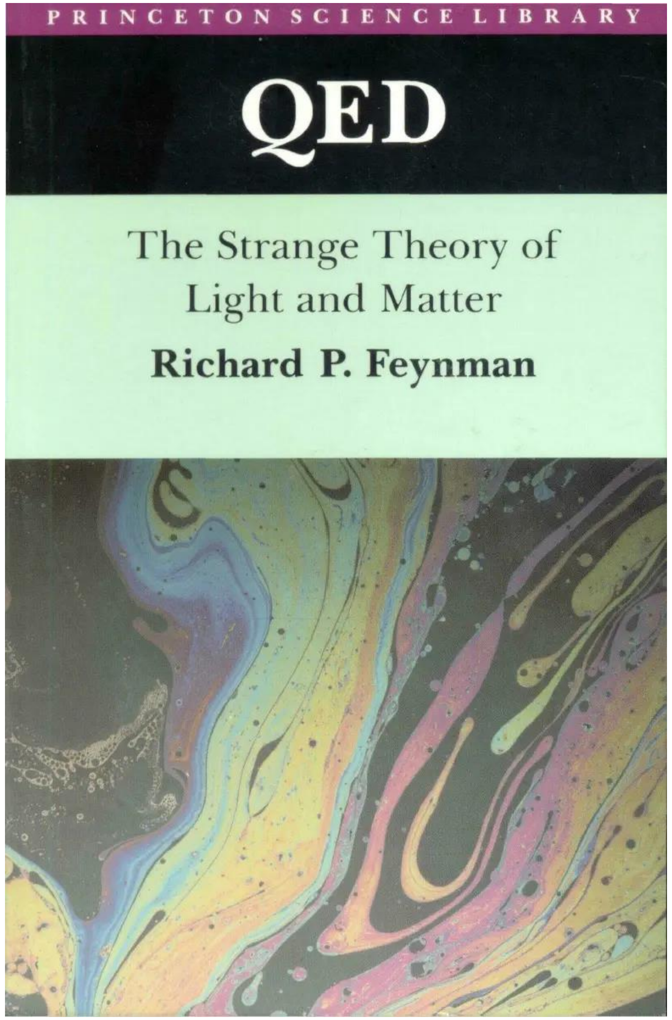
Part I.
A Quick Review of My First QED Talk

Review: 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:
  - Large, comprehensive, and popular: *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)

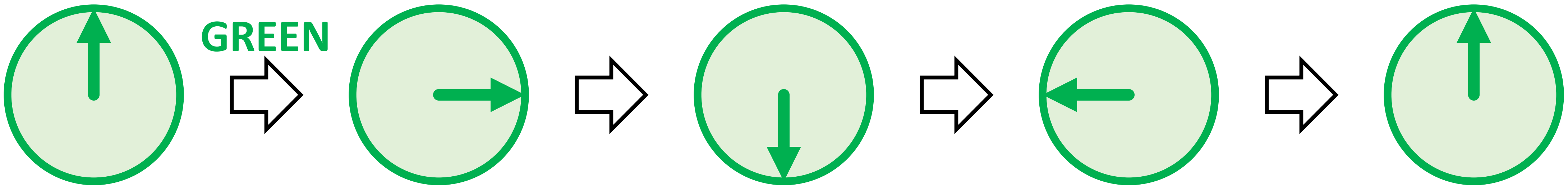
Review: What Is QED?

- 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

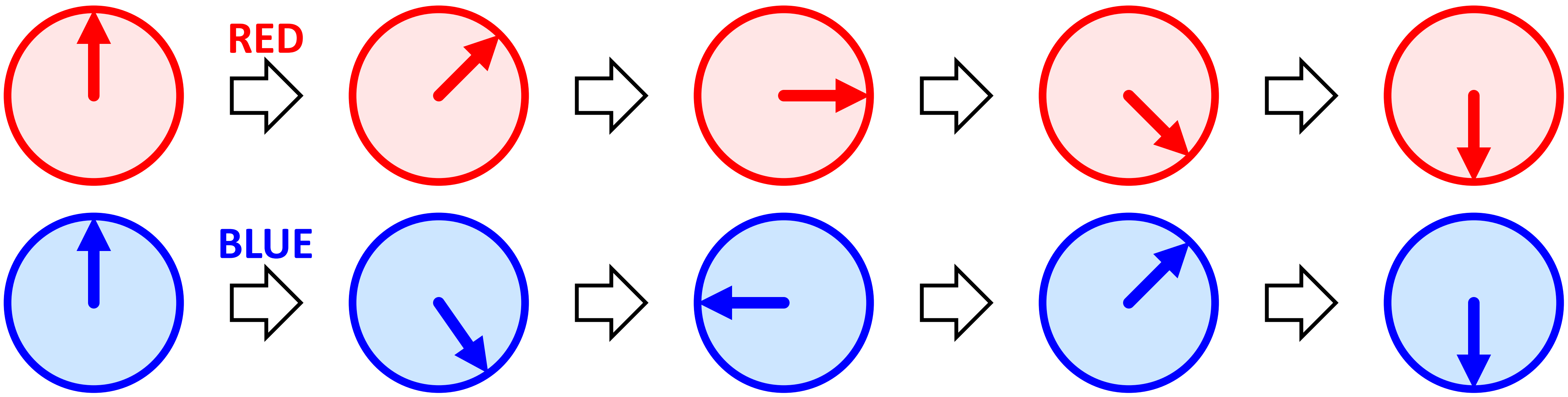


Review: Photons Are Like Stopwatches

Idea #1: As a photon travels, it has an arrow that rotates

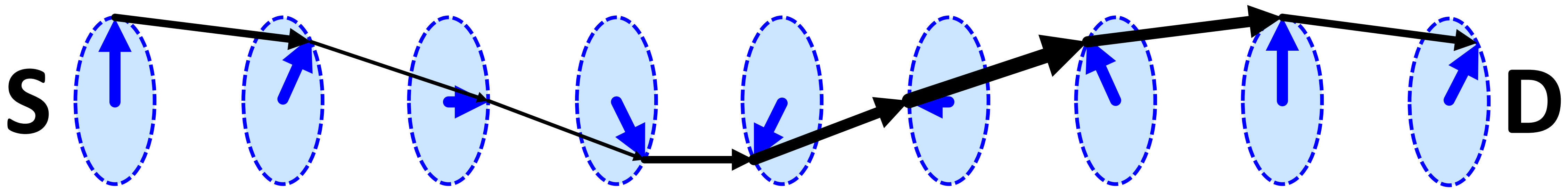


Idea #2: The bluer the light, the faster its arrow rotates as it travels



Review: Photon Paths Resemble Bendable Springs

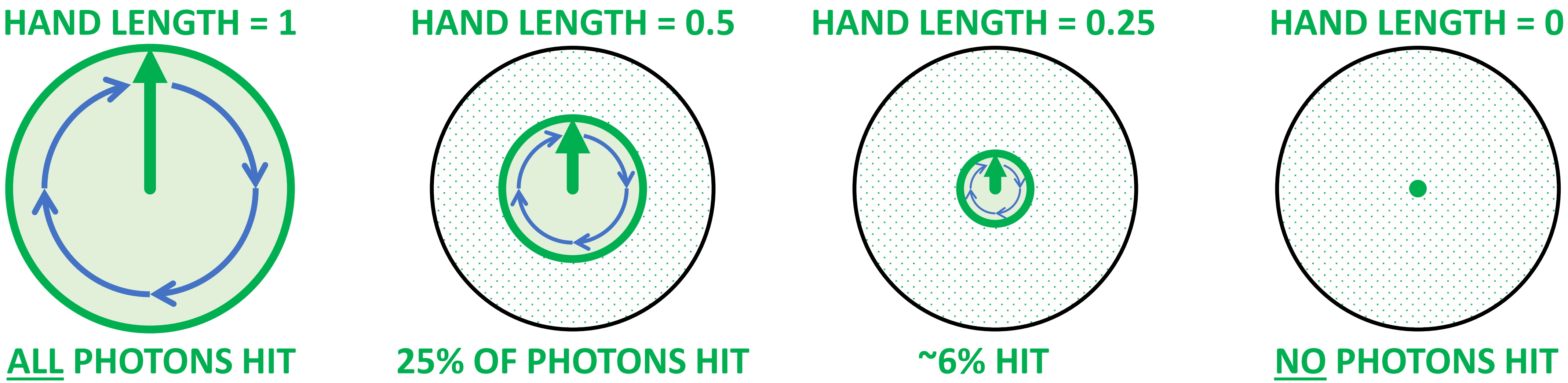
- Each "possible photon path" resembles a long, flexible spring:



- Hidden assumptions:
  - Feynman assumes S and D are static points within a *single* inertial frame
  - The length of a very curvy spring matters, since lightspeed limits apply
  - When elaborated over infinitely many paths with D endings that correspond to "now", the results always converge into a wave model
  - A carefully done wave model thus predicts the same results as QED

Review: Arrow Length Controls Light Intensity

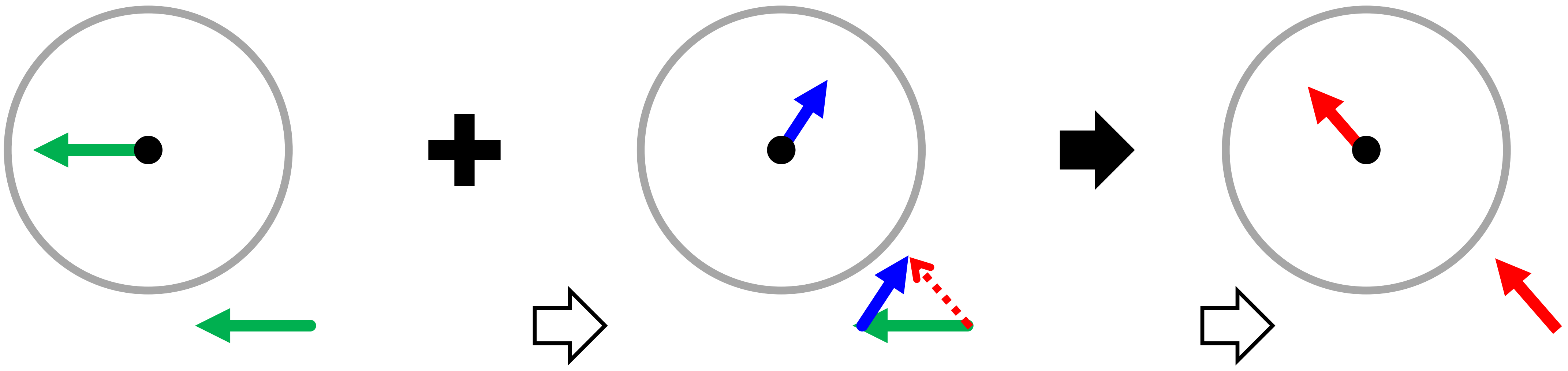
Idea #3: Each photon arrow has a length measured in units of half the clock diameter (radius). This length varies from 1 to 0 radius lengths.



Idea #4: For bright light (many photons), the percentage of dial face swept out by the rotating arrow gives the intensity (brightness) of the light. For *one* photon, this intensity transforms into the **probability** of you seeing that one photon appear as a brief flash of light.

Review: Daisy-Chaining Arrows Adds Them

Idea #5: To analyze a sequence of photon events, string their arrows end-to-end to get a new final length and angle



In Summary... The behavior of photons is remarkably similar to that of ordinary devices such as stopwatches. You *don't* need the full math to understand what is going on conceptually.

Part II.
Reflection: Classical vs. Quantum

Classical Angles of Incidence and Reflection

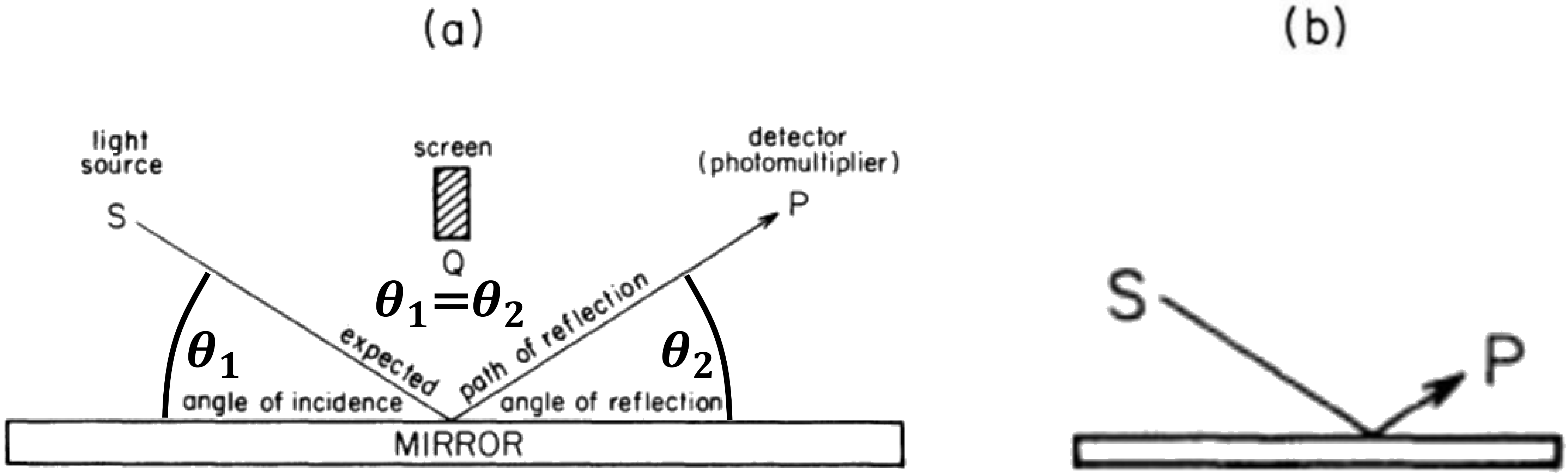


FIGURE 19. The classical view of the world says that a mirror will reflect light where the angle of incidence is equal to the angle of reflection, even if the source and the detector are at different heights, as in (b). [The photons act like balls.]

Quantum Reflection Doesn't Care About Angles (!)

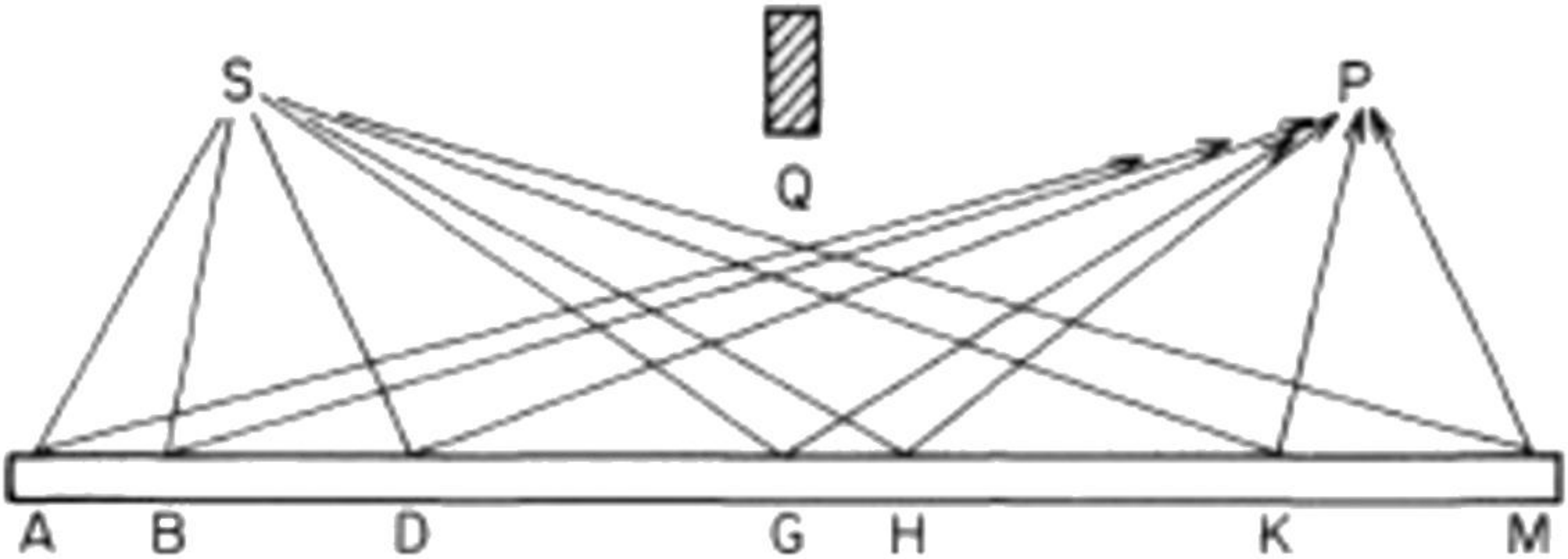


FIGURE 20. The quantum view of the world says that light has an equal amplitude to reflect from **every part** of the mirror, from A to M.

Breaking a Mirror Can Sometimes Be Good Luck

FIGURE 21. To calculate more easily where the light goes, we shall temporarily consider only a strip of mirror divided into little squares, with one path for each square. This simplification in no way detracts from an accurate analysis of the situation.

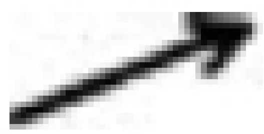


FIGURE 22. Each way the light can go will be represented in our calculation by an arrow of an arbitrary standard length, as shown.

Different Light Paths Have Different Lengths

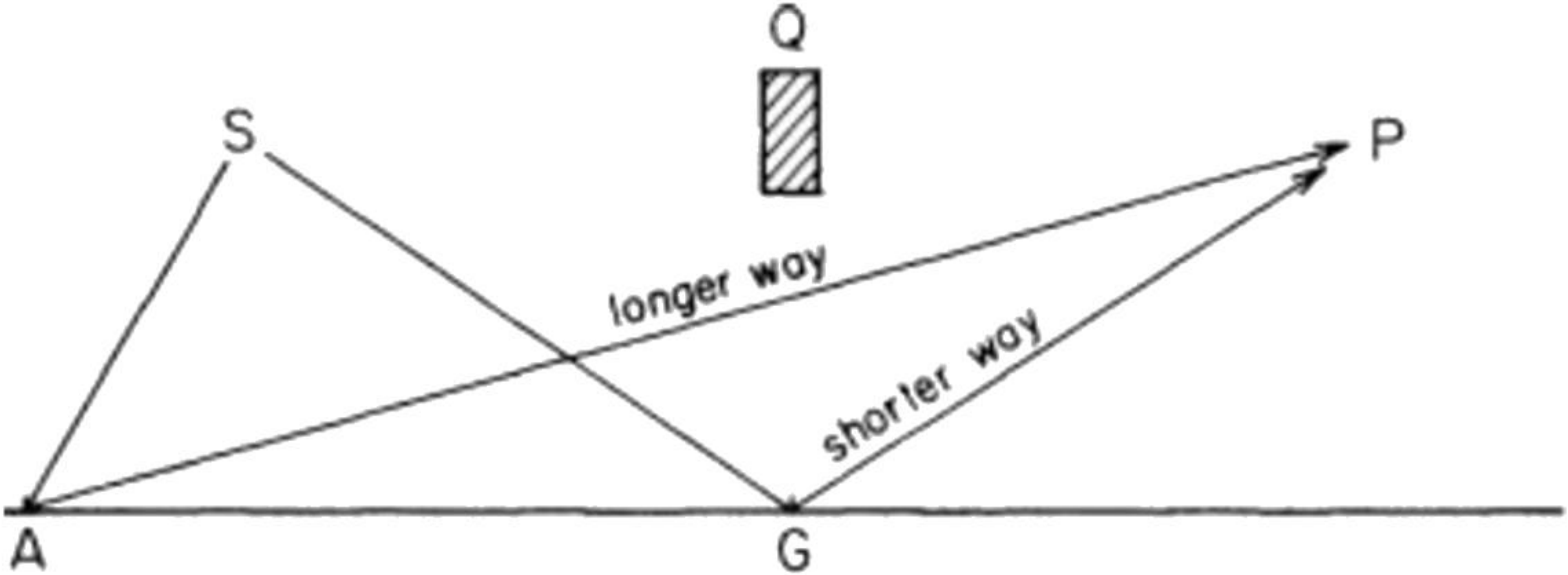


FIGURE 23. While the length of each arrow is essentially the same, the direction will be different because the time it takes for a photon to go on each path is different. Clearly, it takes longer to go from S to A to P than from S to G to P.

Add Arrows for Unique Paths With Different Lengths

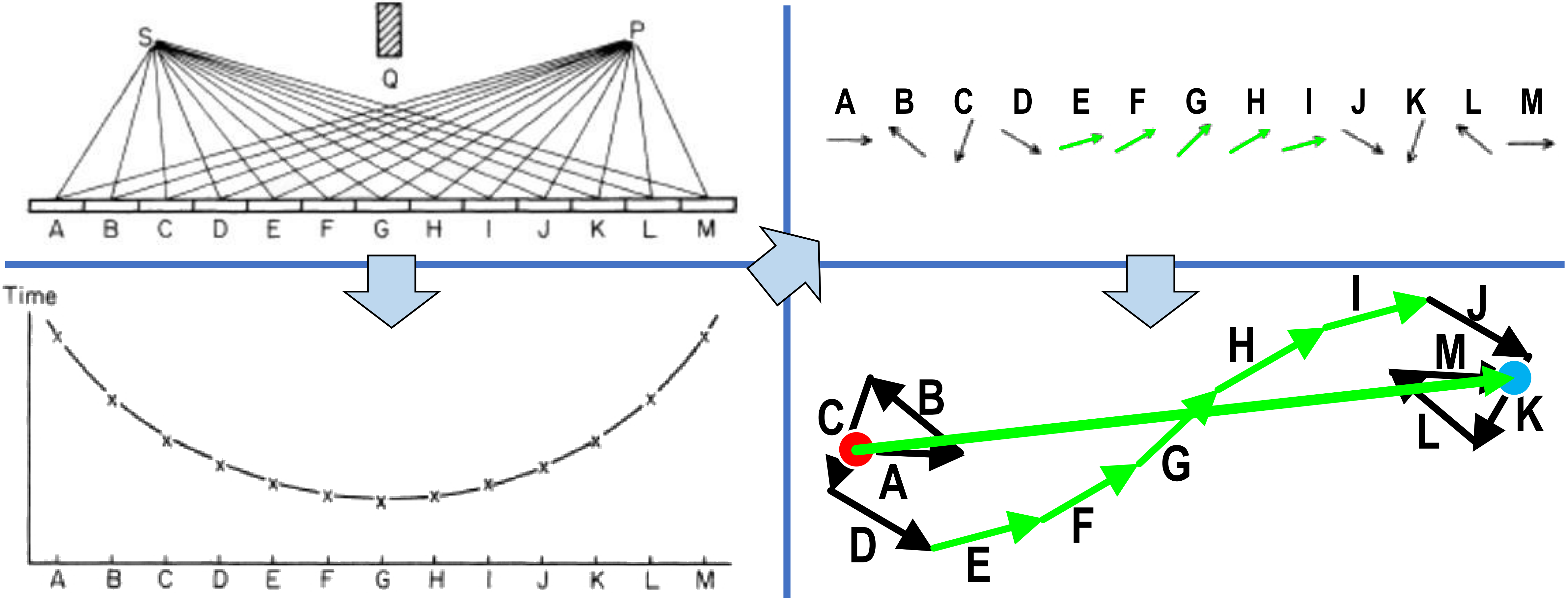


FIGURE 24. Different paths lead to different photon orientations (see next slide)

Adding Photon Arrows for Different-Length Paths

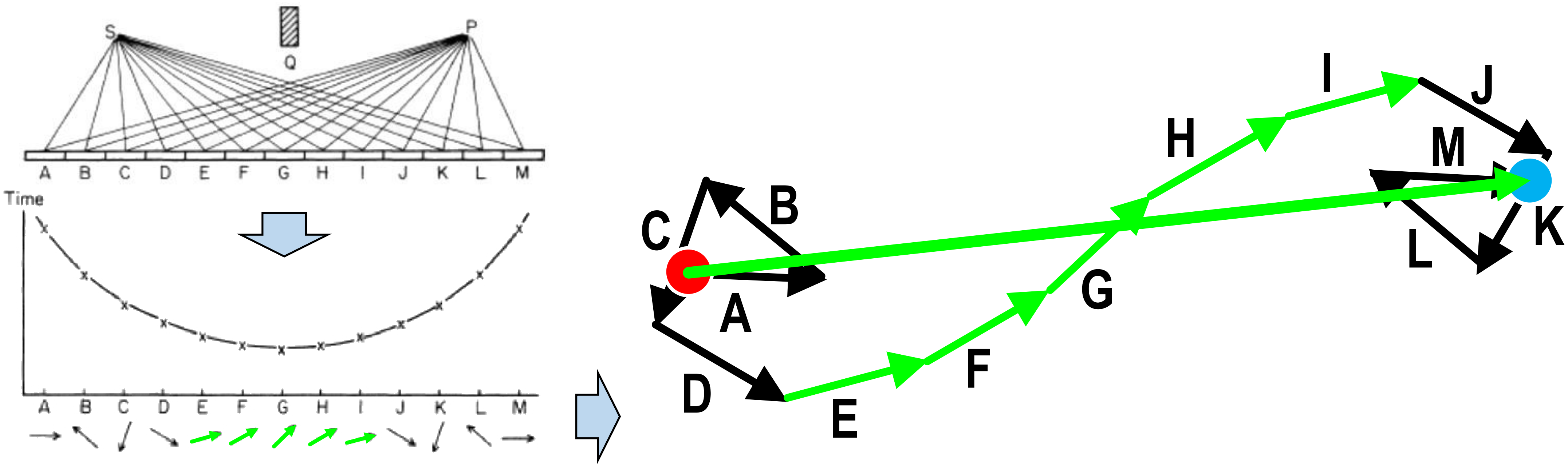


FIGURE 24. Each path the light could go (in this simplified situation) is shown at the top left, with a point on the graph below it showing the time it takes a photon to go from the source to that point on the mirror, and then to the photomultiplier. Below the graph is the direction of each arrow, and on the right is the result of the end-to-end chain addition of all the arrows. It is evident that the major contribution to the final arrow's length is made by arrows **E** through **I**, whose directions are nearly the same because the timing of their paths is nearly the same. This also happens to be where the total time is least. It is therefore approximately right to say that light goes where the time is least.

Part III.
How To Stay Invisible: Spin In Circles

The Majority of Reflected Light Spins in Circles

FIGURE 25. To test the idea that there is really reflection happening at the ends of the mirror (but it is just cancelling out), we do an experiment with a large piece of mirror that is located in the wrong place for reflection from S to P. This piece of mirror is divided into much smaller sections, so that the **timing from one path to the next is not very different.** When all the arrows are added, they get nowhere: **they go in a circle and add up to nearly nothing**.

Proving That Photons Reflect from the Entire Mirror

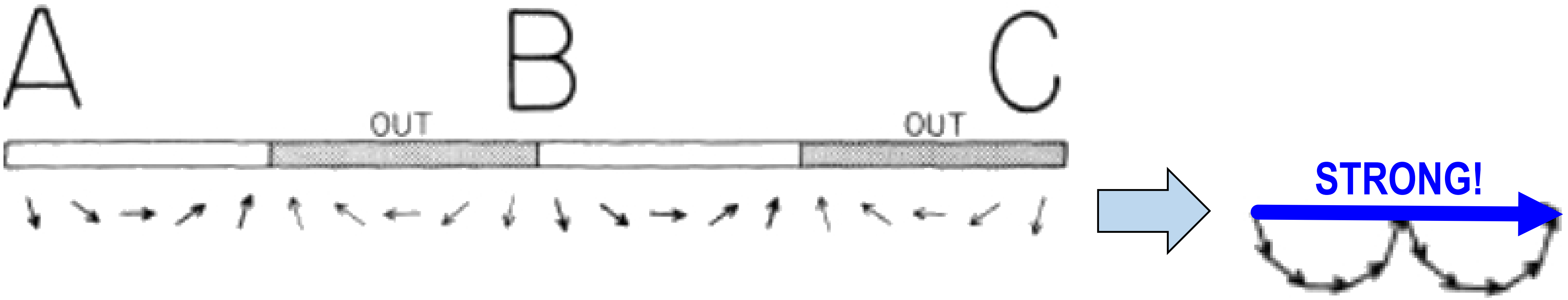


FIGURE 26. If only the arrows with a bias in a particular direction — such as to the right — are added, while the others are disregarded (by etching away the mirror in those places), then a substantial amount of light reflects from this piece of mirror located in the wrong place. Such an etched mirror is called a **diffraction grating**.

Part IV.
Diffraction Gratings, Large and Small

Diffraction Grating Reflections Distinguish Colors

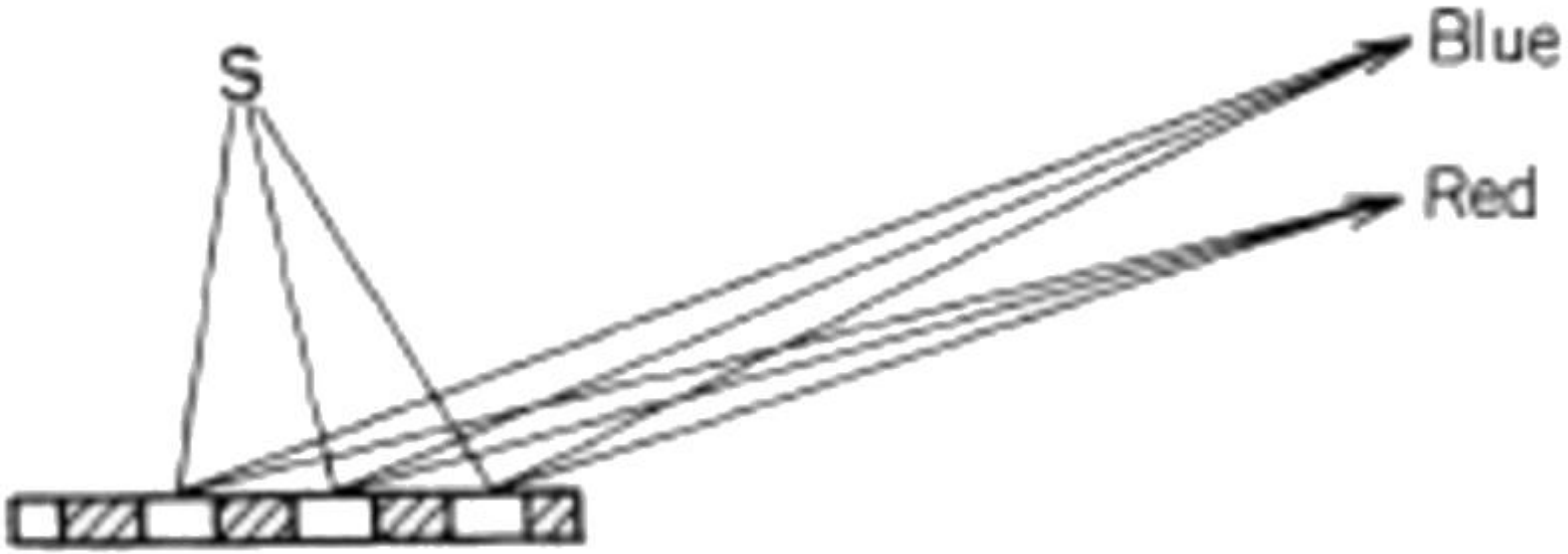


FIGURE 27. A diffraction grating with grooves at the right distance for red light also works for other colors, if the detector is in a different place. Thus, it is possible to see different colors reflecting from a grooved surface — such as a phonograph record — depending on the angle.

Crystals Can Also Be Diffraction Gratings

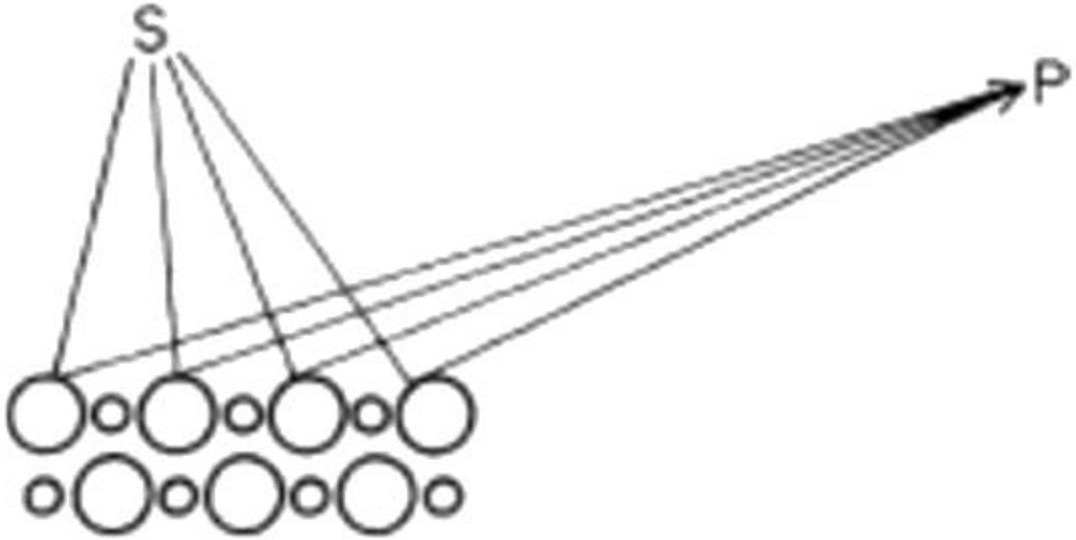


FIGURE 28. Nature has made many types of diffraction gratings in the form of crystals. A salt crystal reflects X-rays (light for which the imaginary stopwatch hand moves extremely fast — perhaps 10,000 times faster than for visible light) at various angles, from which can be determined the exact arrangement and spacings of the individual atoms.

Part V.
The Shortest-Path Cleverness of Photons

Adding Photon Paths for Water Reflection

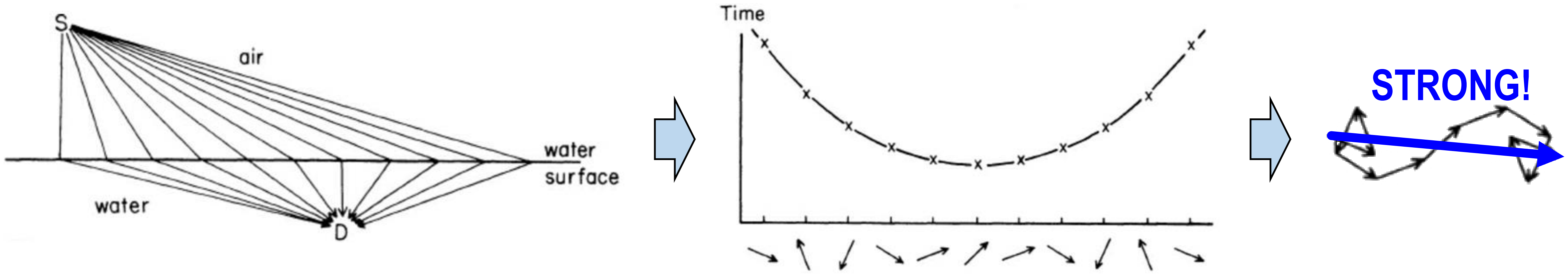


FIGURE 29. Quantum theory says that light can go from a source in air to a detector in water in many ways. If the problem is simplified as in the case of the mirror, a graph showing the timing of each path can be drawn, with the direction of each arrow below it. Once again, the major contribution toward the length of the final arrow comes from those paths whose arrows point in nearly the same direction because their timing is nearly the same; **once again, this is where the time is least**.

Photons Find the Best Paths Faster than People

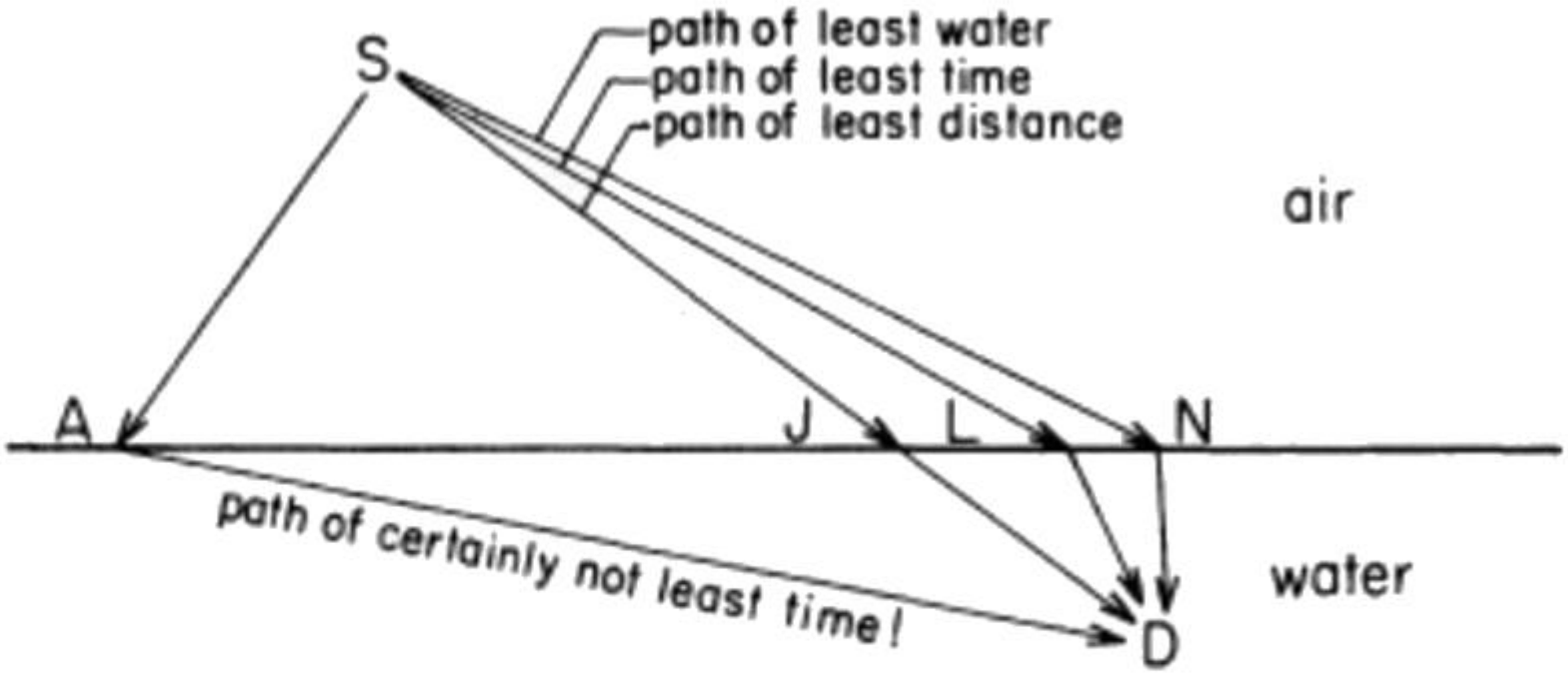


FIGURE 30. Finding the path of least time for light is like finding the path of least time for a lifeguard running and then swimming to rescue a drowning victim: the path of least distance has too much water in it; the path of least water has too much land in it; the **path of least time is a compromise** between the two.

Even Mirages Use Fastest-Time Photons

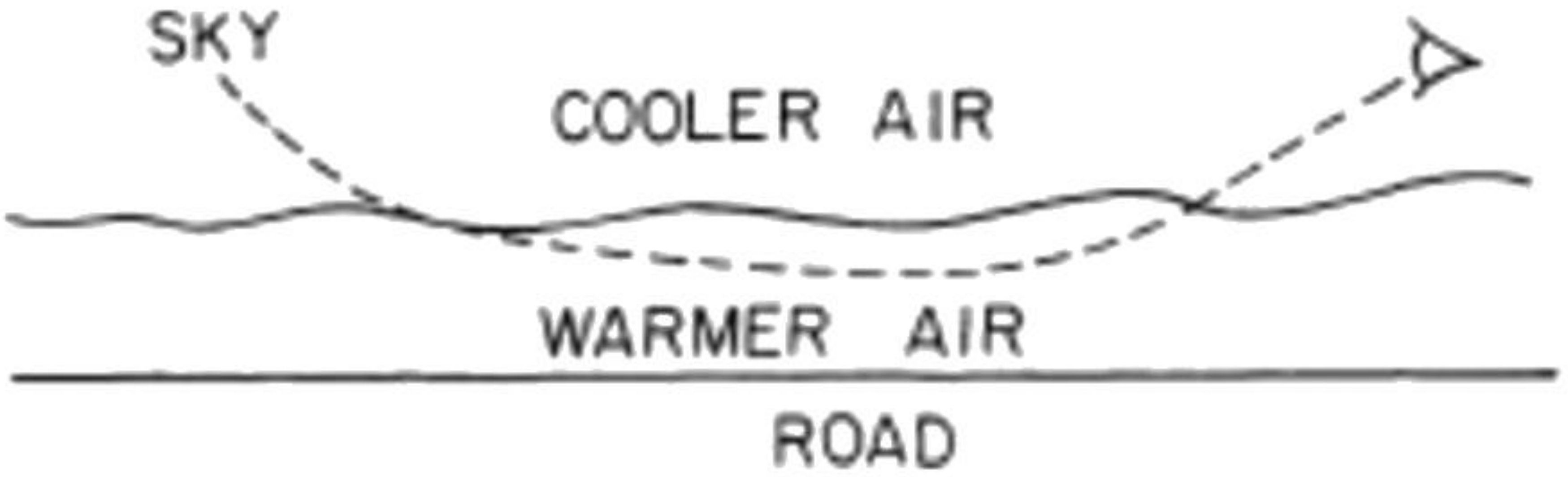


FIGURE 31. Finding the path of least time explains how a mirage works. Light goes faster through warm air than through cool air. Some of the sky appears to be on the road because some of the light from the sky reaches the eye by coming up from the road. The only other time sky appears to be on the road is when water is reflecting it, and thus **a mirage appears to be water**.

Photons Don’t *Have* to Travel in Straight Lines (!)

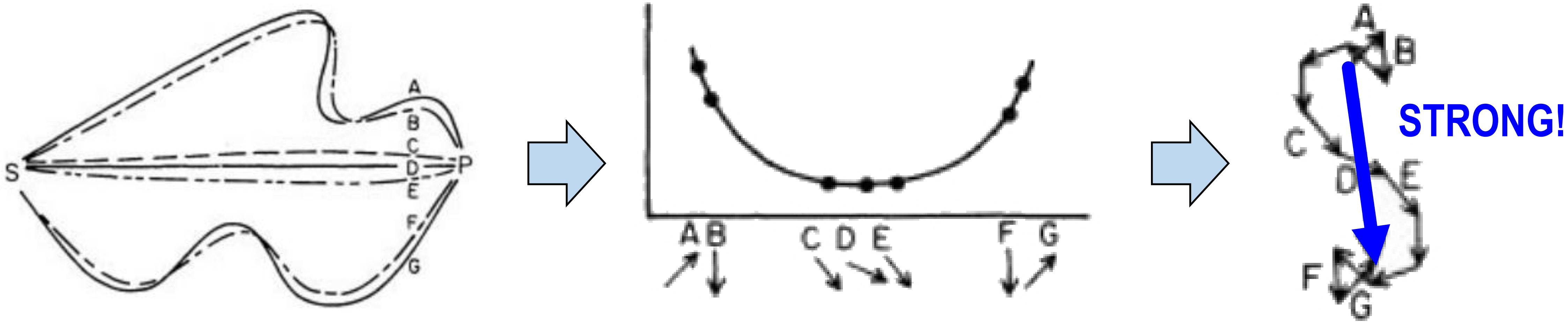


FIGURE 32. Quantum theory can be used to show why light appears to travel in straight lines. When all possible paths are considered, each crooked path has a nearby path of considerably less distance and therefore much less time (and a substantially different direction for the arrow). Only the paths near the straight-line path at *D* have arrows pointing in nearly the same direction, because their timings are nearly the same. Only such arrows near the straightest path count, because it is from them that we accumulate a large final arrow.

Part VI.
Why Lasers Go Straight, But Not Photons

Light Explores Nearby Paths (Many = Straight)

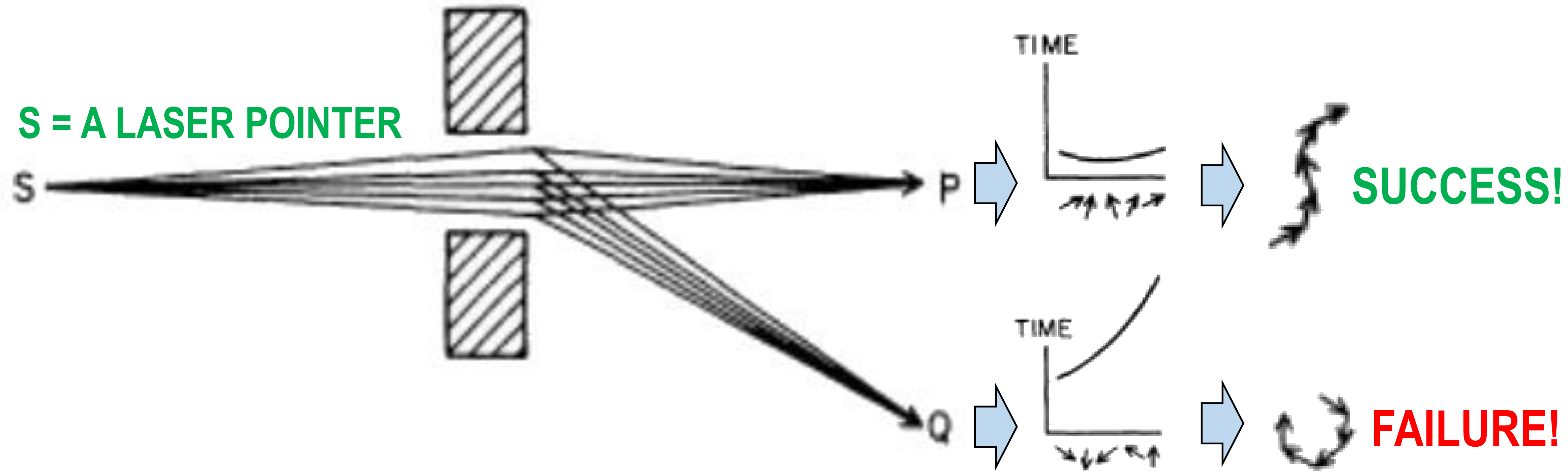


FIGURE 33. Light travels not just in the straight line, but in the nearby paths as well. When two blocks are separated enough to allow for these nearby paths, the photons proceed normally to P and hardly ever go to Q.

Why Light Spreads Out After Narrow Apertures

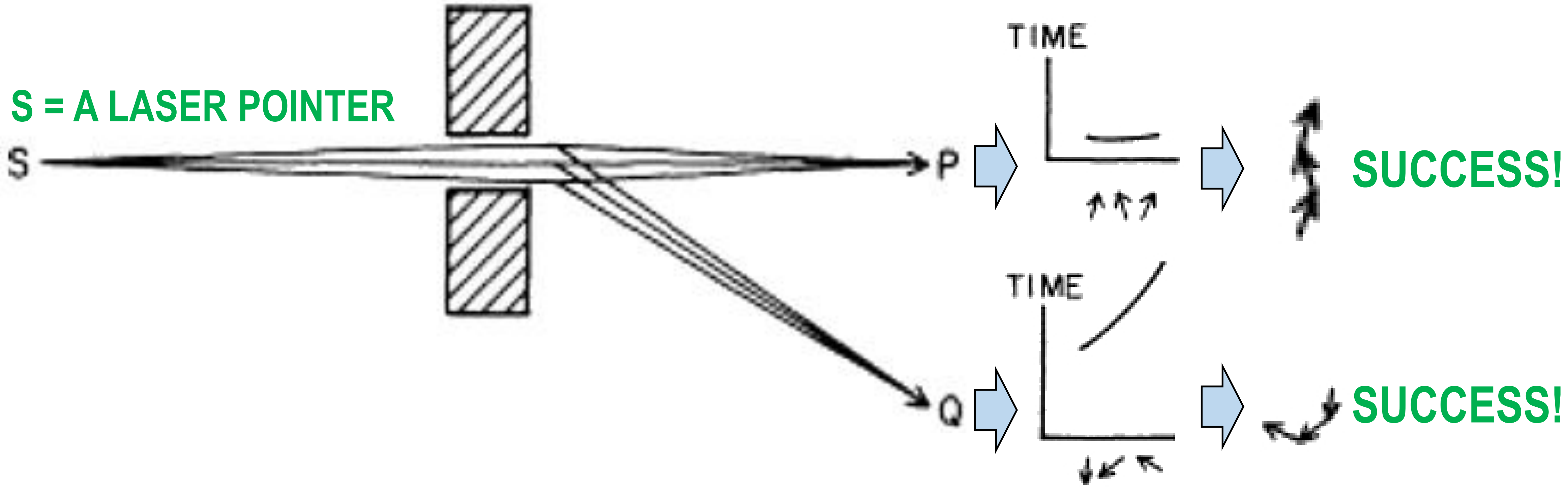


FIGURE 34. When light is restricted so much that only a few paths are possible, the light that is able to get through the narrow slit goes to Q almost as much as to P, because there are not enough arrows representing the paths to Q to cancel each other out.

Part VII.
How Focusing Lenses Work

Assuming Straight Paths Simplifies the Analysis

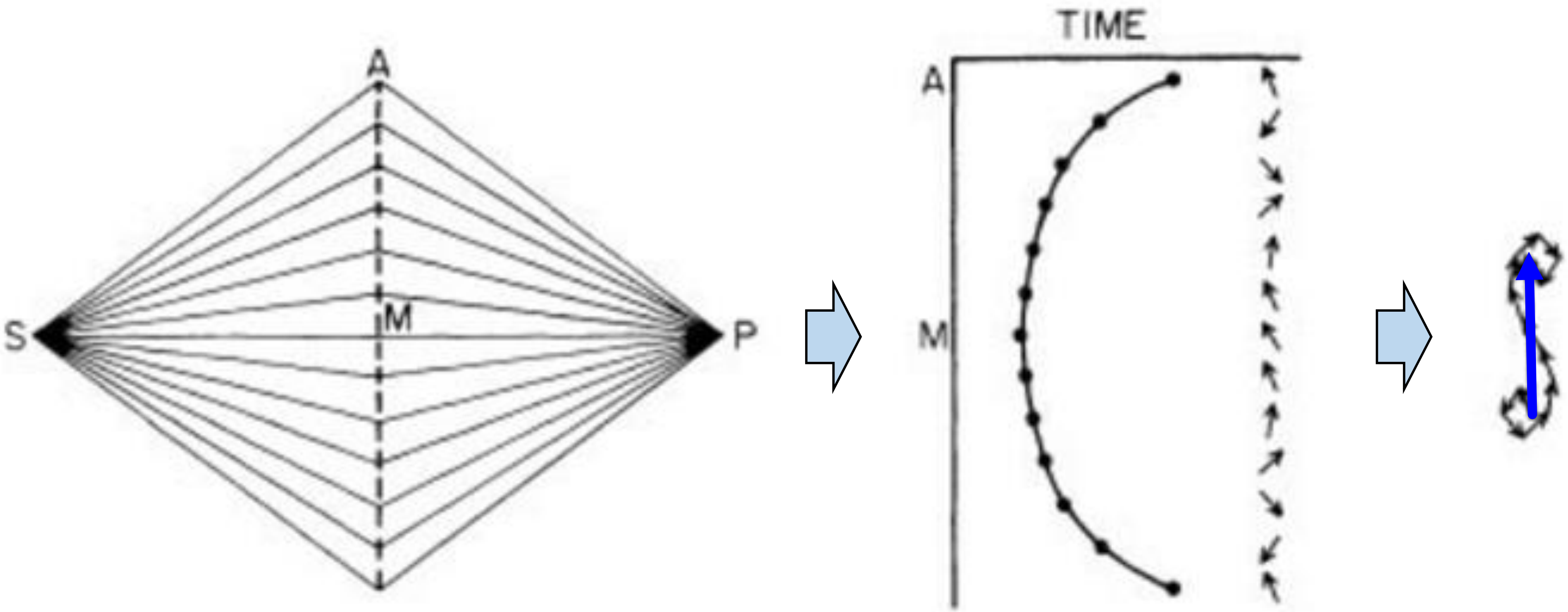


FIGURE 35. The analysis of all possible paths from S to P is simplified to include only broken pairs of straight lines in a single plane. The effect is the same as in the more complicated, real case where true straight paths do not exist: there is a time curve with a minimum, where most of the contribution to the final arrow is made.

Glass Lenses Play Tricks on Photon Arrow Sums

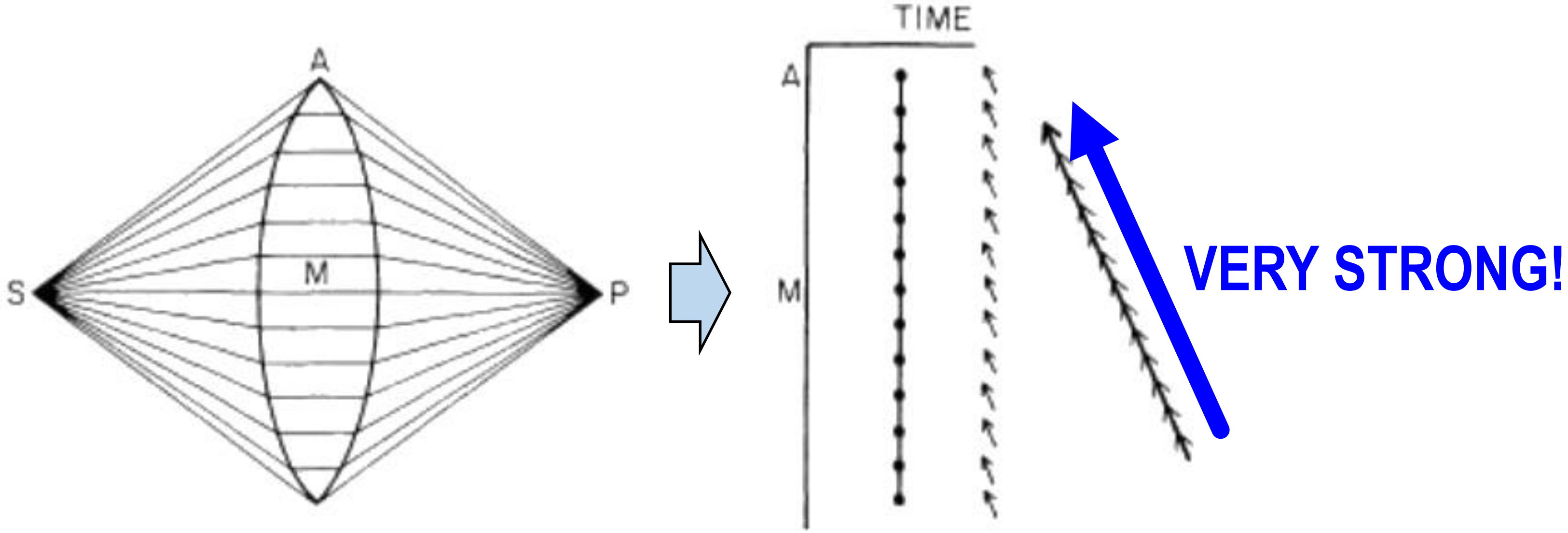


FIGURE 36. A “trick” can be played on Nature by slowing down the light that takes shorter paths: glass of just the right thickness is inserted so that all the paths will take exactly the same time. This causes all of the arrows to point in the same direction, and to produce a whopping final arrow — lots of light! Such a piece of glass made to greatly increase the probability of light getting from a source to a single point is called a focusing lens.

Part VIII.
How to Calculate Sequences of Events

Using Multiplication for Sequences of Photon Events

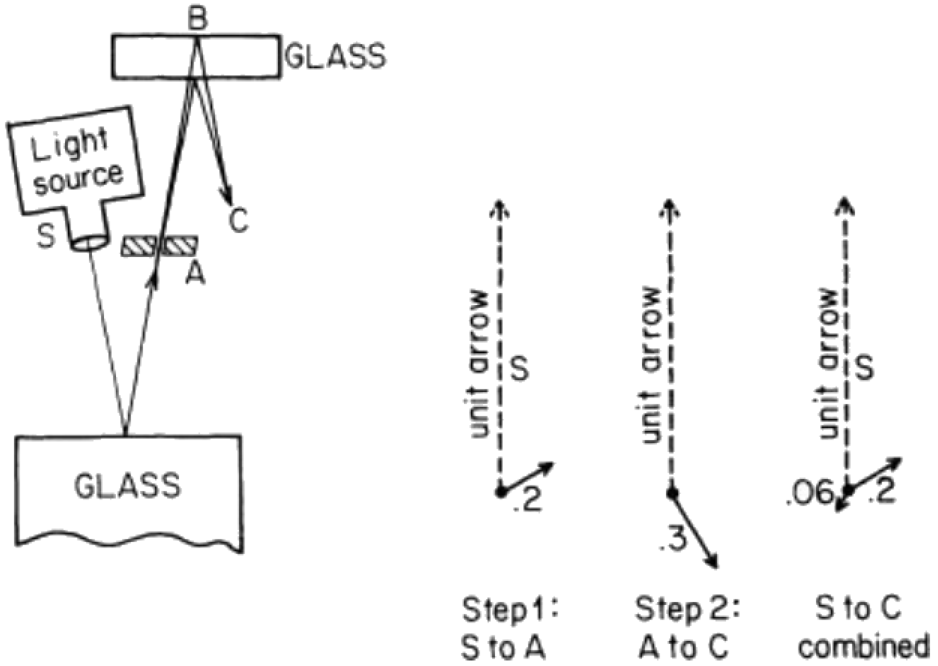


FIGURE 37. A **compound photon event** can be analyzed as a **succession of steps**. In this example, the photon path from S to C can be divided into two steps: 1) a photon gets from S to A, and 2) the photon gets from A to C. Each **step** can be analyzed separately to produce an arrow that can be regarded in a new way: as a unit arrow (an arrow of length 1 pointed at 12 o'clock) that has gone through a **shrink and turn**. In this example, the shrink and tum for Step 1 are 0.2 and 2 o'clock; the shrink and tum for Step 2 are 0.3 and 5 o'clock. To get the amplitude for the two steps in succession, we **shrink and turn in succession**: the unit arrow is shrunk and turned to produce an arrow of length 0.2 turned to 2 o'clock, which itself is shrunk and turned (as if it were the unit arrow) by 0.3 and 5 o'clock to produce an arrow of length 0.06 and turned to 7 o'clock. This process of successive shrinking and turning is called **"multiplying" arrows**.

Multiplying Lines by Scaling Their Lengths

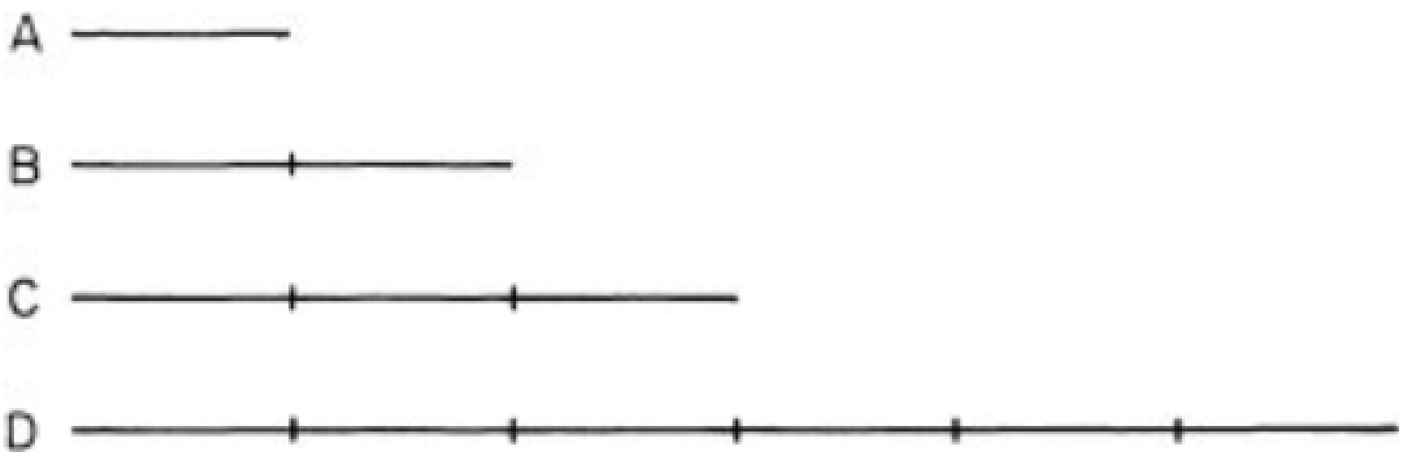


FIGURE 38. We can express any number as a transformation of the unit line through expansion or shrinkage. If A is the unit line, then B represents 2 (expansion), and C represents 3 (expansion). Multiplying lines is achieved through successive transformations. For example, multiplying 3 by 2 means that the unit line is expanded 3 times and then 2 times, producing the answer, an expansion of 6 (line D). If D is the unit line, then line C represents 1/2 (shrinkage), line B represents 1/3 (shrinkage), and multiplying 1/2 by 1/3 means the unit line D is shrunk to 1/2, and then to 1/3 of that, producing the answer, a shrinkage to 1/6 (line A).

Multiplying as a Series of Arrow Shrinks and Turns

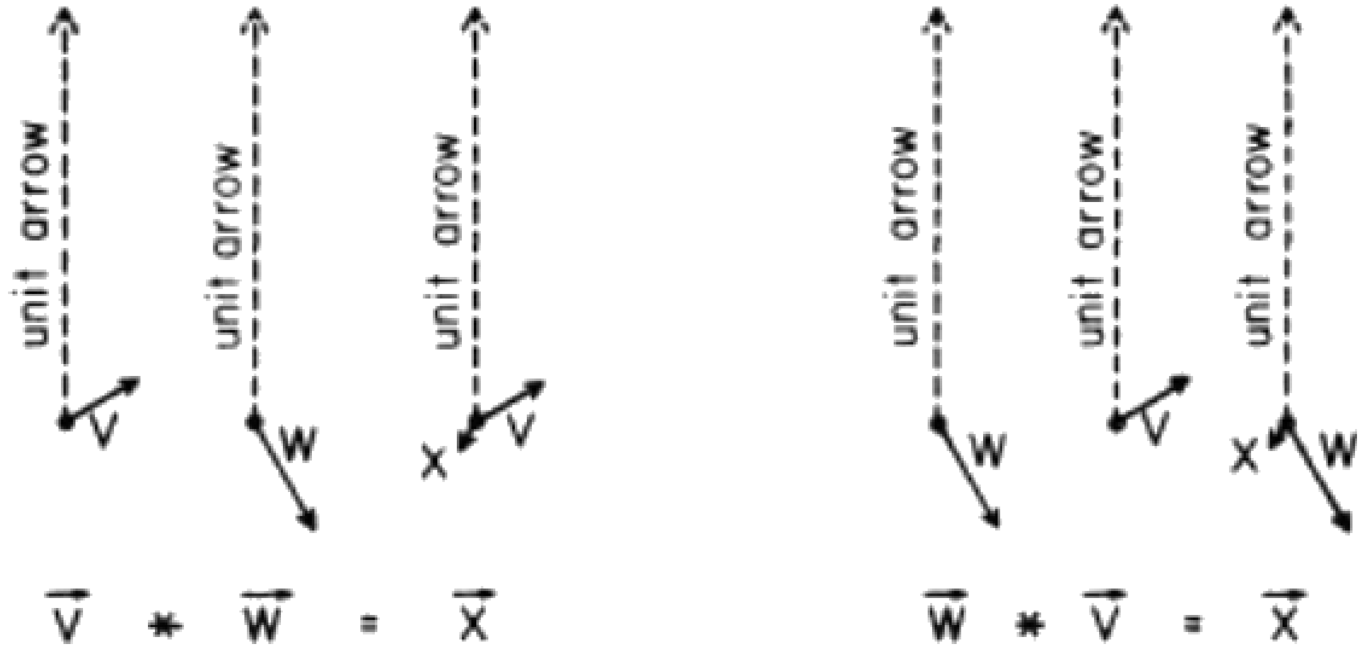


FIGURE 39. Mathematicians found that multiplying arrows can also be expressed as successive transformations (for our purposes, successive shrinks and turns) of the unit arrow. As in normal multiplication, the order is not important: the answer, arrow X, can be obtained by multiplying arrow V by arrow W or arrow W by arrow V.

Part IX.
A Game of Conservation and Exploration

A More Detailed Look at Surface Reflection

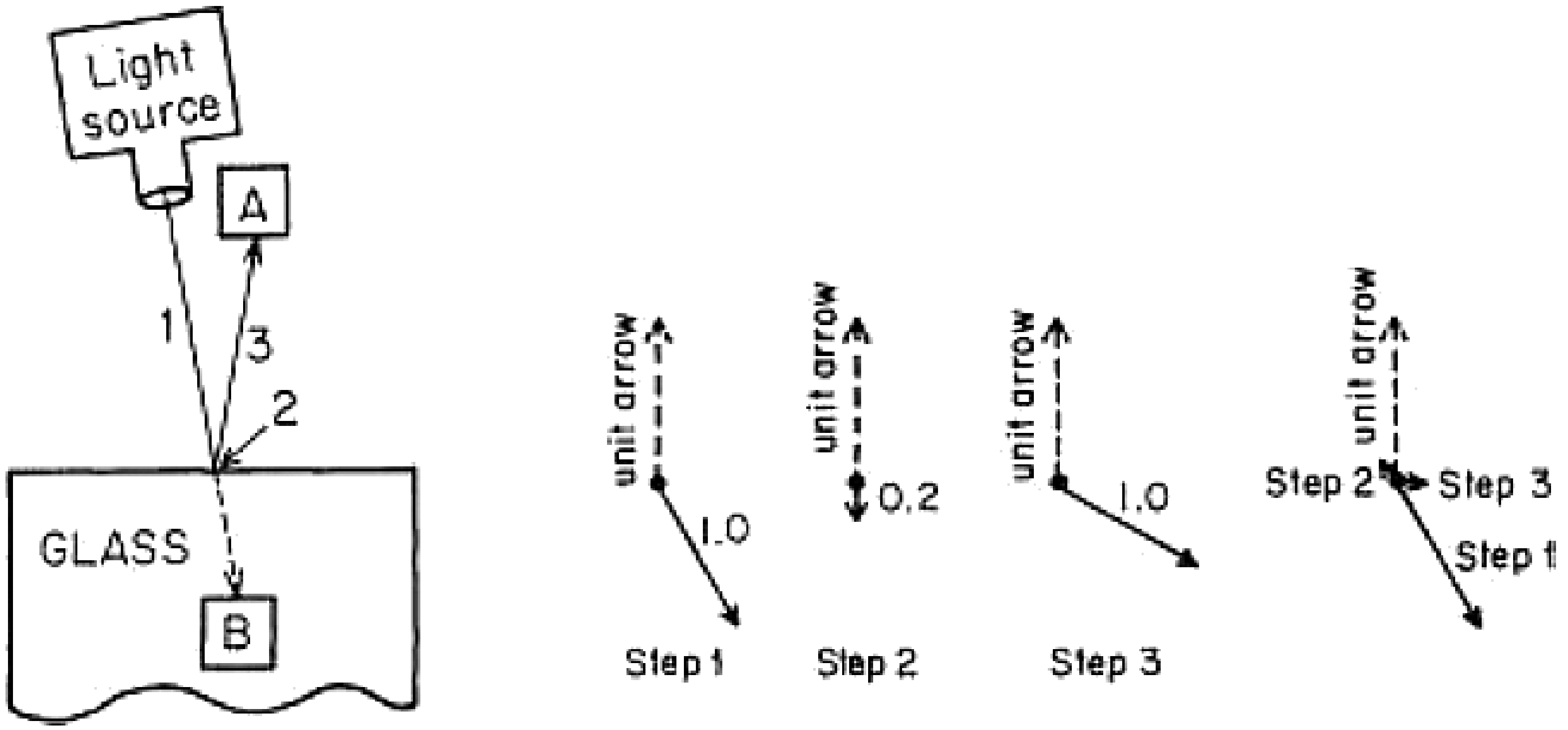


FIGURE 40. Reflection by a single surface can be divided into three steps, each with a shrink and/or turn of the unit arrow. The net result, an arrow of length 0.2 pointed in some direction, is the same as before, but our method of analysis is more detailed now.

An Example of 96% Surface Transmission

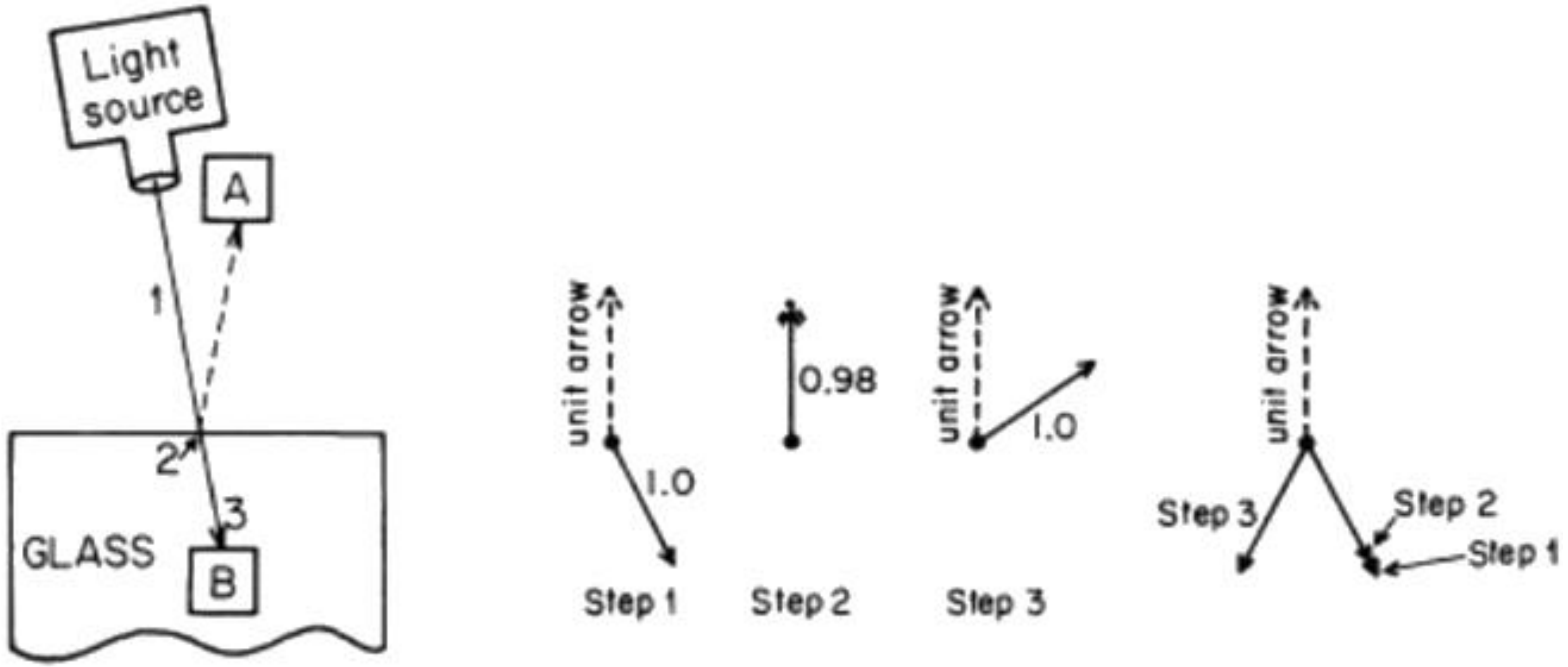


FIGURE 41. Transmission by a single surface can also be divided into three steps, with a shrink and/ or turn for each step. An arrow of length 0.98 has a square of about 0.96, representing a probability of transmission of 96% (which, combined with the 4% probability of reflection, accounts for 100% of the light).

Reflection from the Back Surface: Seven Steps

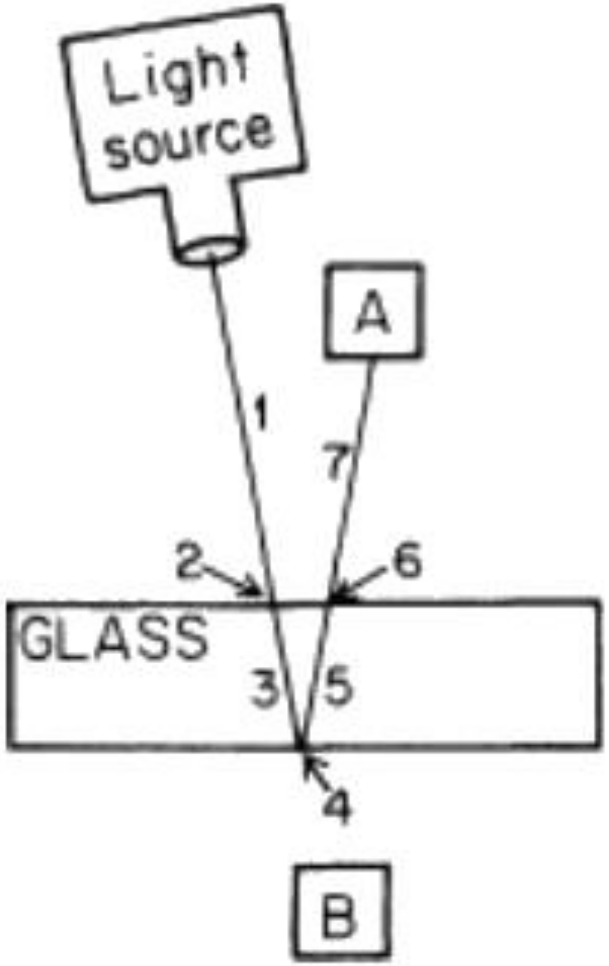


FIGURE 42. Reflection from the back surface of a layer of glass can be divided into seven steps. Steps 1, 3, 5, and 7 involve turning only; steps 2 and 6 involve shrinks to 0.98, and step 4 involves a shrink to 0.2. The result is an arrow of length 0.192 — which was approximated as 0.2 in the first lecture — turned at an angle that corresponds to the total amount of turning by the imaginary stopwatch hand.

Transmission and Reflection Must Stay Linked!

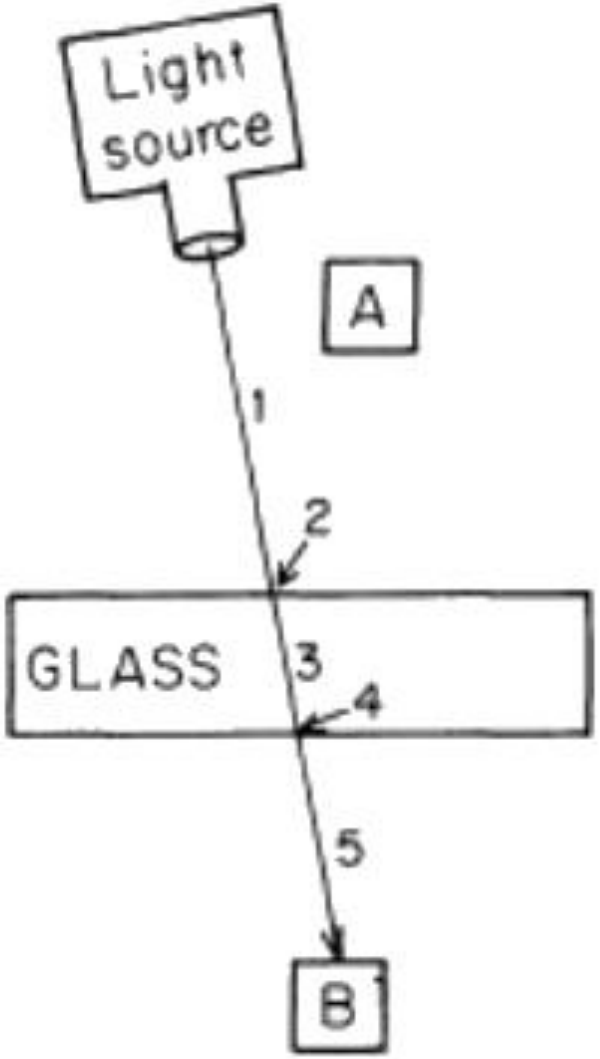


FIGURE 43. Transmission by two surfaces can be broken down into five steps. Step 2 shrinks the unit arrow to 0.98, step 4 shrinks the 0.98 arrow to 0.98 of that (about 0.96); steps 1, 3, and 5 involve turning only. The resulting arrow of length 0.96 has a square of about 0.92, representing a probability of transmission by two surfaces of 92% (which corresponds to the expected 8% reflection, which is right only “twice a day”). When the thickness of the layer is right to produce a probability of 16% reflection, with a 92% probability of transmission, 108% of the light is accounted for! **Something is wrong with this analysis!**

A Reflection that Keeps Transmission Correct

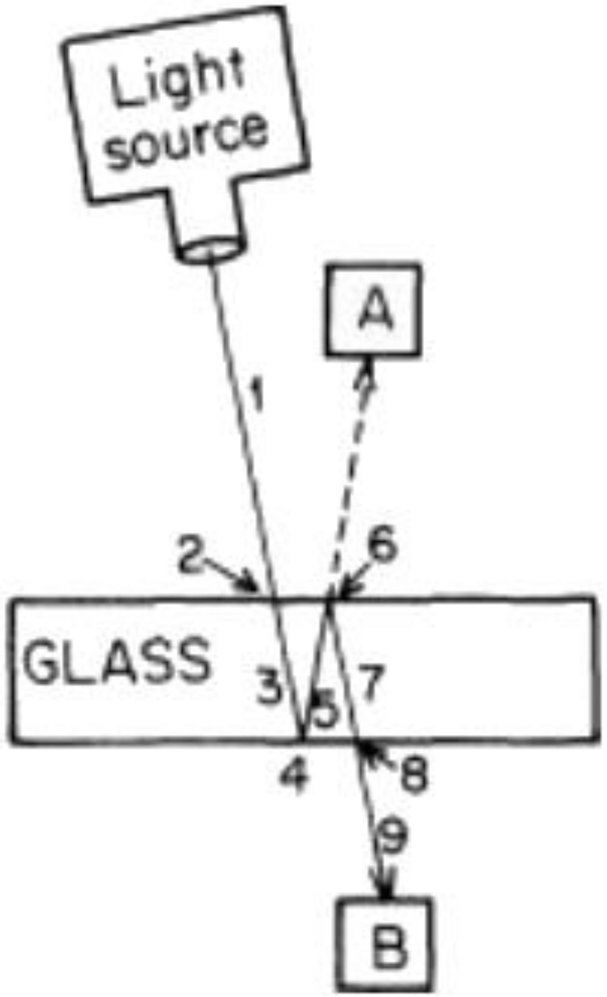


FIGURE 44. Another way that light could be transmitted by two surfaces must be considered in order to make the calculation more accurate. This path involves two shrinks of 0.98 (steps 2 and 8) and two shrinks of 0.2 (steps 4 and 6), resulting in an arrow of length 0.0384 (rounded off to 0.04).

Arrow Transformations Always Conserve Energy

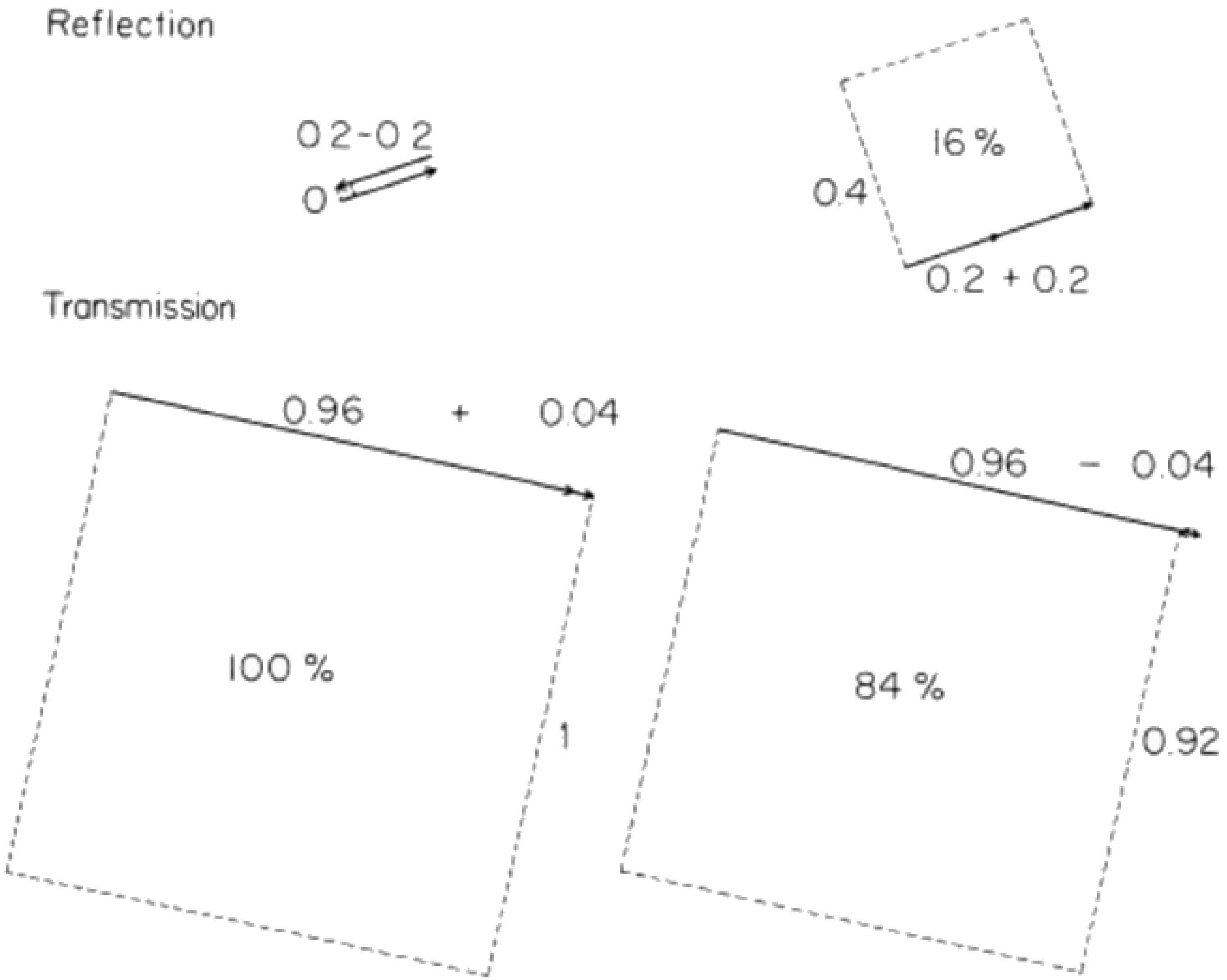


FIGURE 45. Nature always makes sure 100% of the light is accounted for. When the thickness is right for the transmission arrows to accumulate, the arrows for reflection oppose each other; when the arrows for reflection accumulate, the arrows for transmission oppose each other.

Any Reflection that *Can* Happen, *Will* Happen

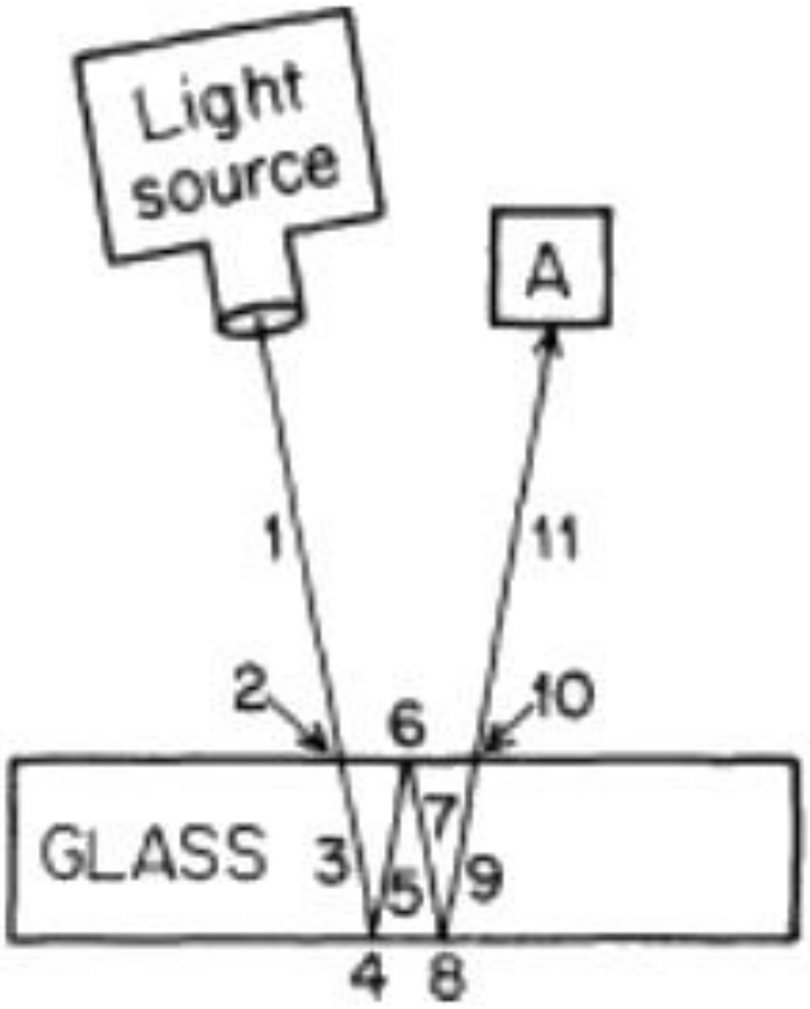


FIGURE 46. Yet other ways the light could reflect should be considered for a more accurate calculation. In this figure, shrinks of 0.98 occur at steps 2 and 10; shrinks of 0.2 occur at steps 4, 6, and 8. The result is an arrow with a length of about 0.008, which is another alternative for reflection, and should therefore be added to the other arrows that represent reflection (0.2 for the front surface and 0.192 for the back surface).

Part X.
Cases Involving Multiple Photons

If Multiple Unique Photons Are Involved, Multiply

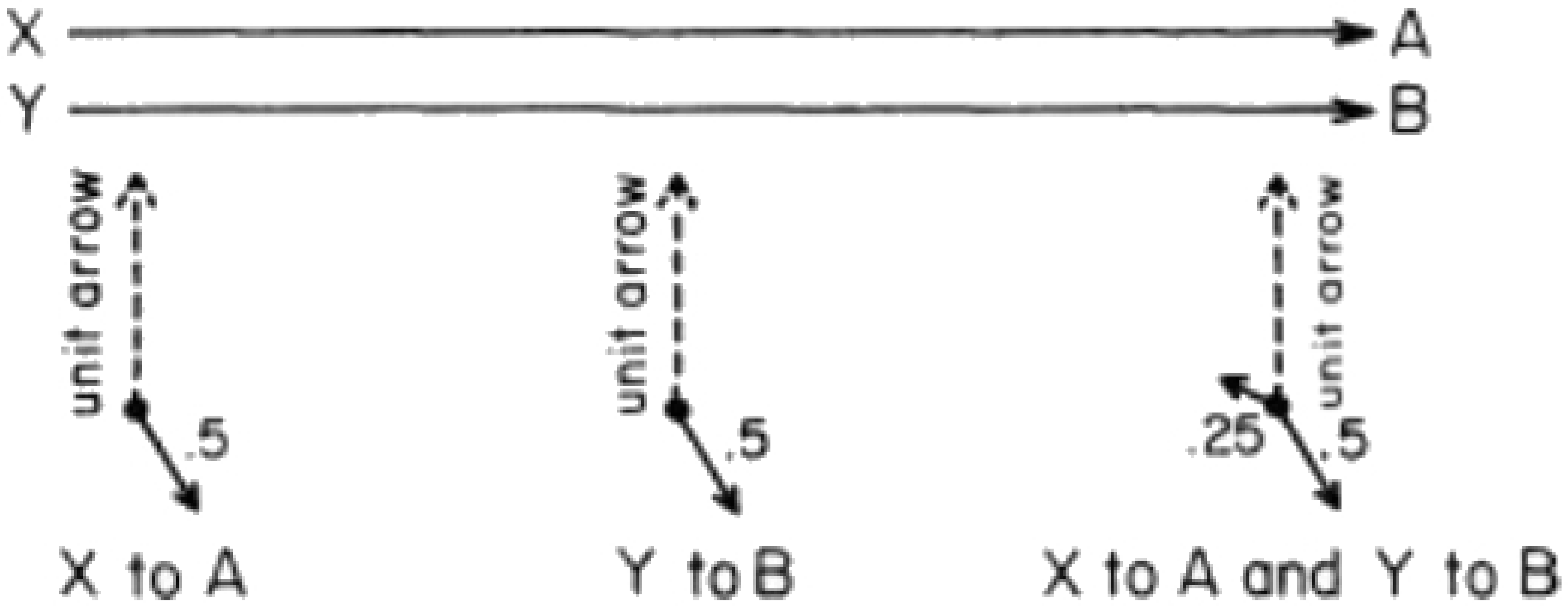


FIGURE 47. If one of the ways a particular event can happen depends on a number of things happening independently, the amplitude for this way is calculated by multiplying the arrows of the independent things. In this case, the final event is: after sources X and Y each lose a photon, photomultipliers A and B make a click. One way this event could happen is that a photon could go from X to A and a photon could go from Y to B (two independent things). To calculate the probability for this "first way, the arrows for each independent thing — X to A and Y to B — are multiplied to produce the amplitude for this particular way. (Analysis continued in Fig. 48.)

Multi-Photon Events Still Add to a Single Arrow

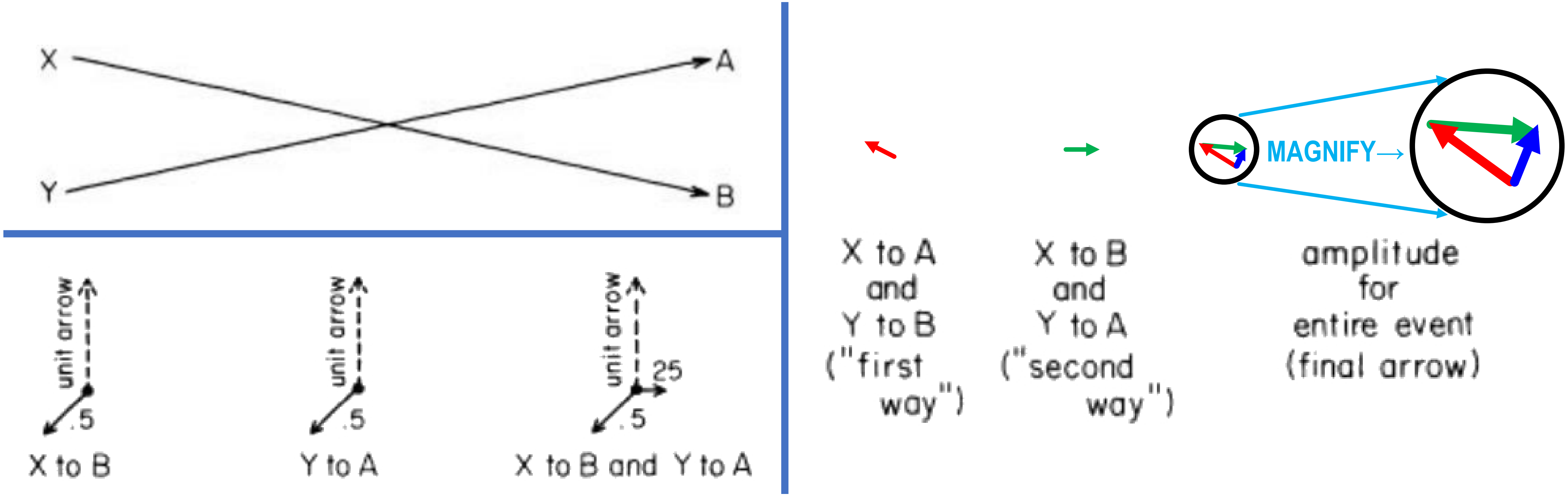


FIGURE 48. The other way the event described in Figure 47 could happen — a photon goes from X to B, and a photon goes from Y to A — also depends on two independent things happening, so the amplitude for this "second way" is also calculated by multiplying the arrows of the independent things. The "first way" and "second way" arrows are ultimately added together, resulting in the final arrow for the event. The probability of an event is always represented by a single final arrow — no matter how many arrows were drawn, multiplied, and added to achieve it.

Part XI.
The Double-Slit Experiment with Photons

Interference With Two Holes (Two-Slit Experiment)

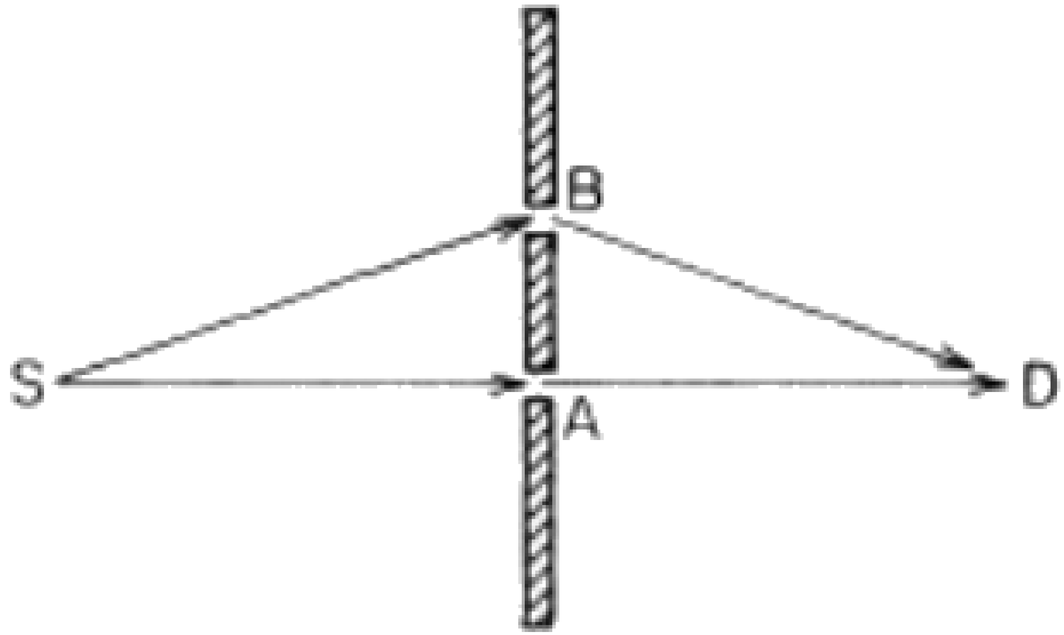


FIGURE 49. Two tiny holes (at A and B) in a screen that is between a source S and a detector D let nearly the same amount of light through (in this case, 1%) when one or the other hole is open. When both holes are open, "interference" occurs: the detector clicks from zero to 4% of the time, depending on the separation of A and B — shown in Figure 51(a).

Trying to Spot Which Way the Photon Went

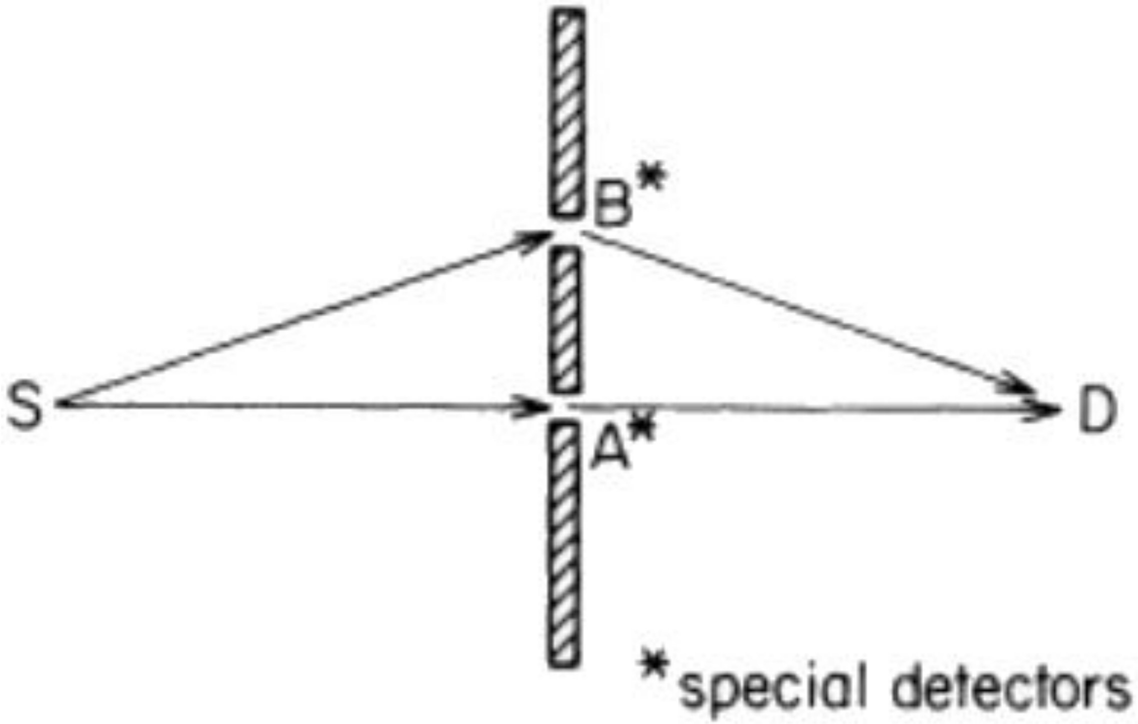


FIGURE 50. When special detectors are put in at A and B to tell which way the light went when both holes are open, the experiment has been changed. Because a photon always goes through one hole or the other (when you are checking the holes), there are two distinguishable final conditions: 1) the detectors at A and D go off, and 2) the detectors at B and D go off. The probability of either event happening is about 1 %. The probabilities of the two events are added in the normal way, which accounts for a 2% probability that the detector at D goes off — shown in Figure 51(b).

Part XII.
No History = Maximum Interference

Interference Occurs Only When No Record Exists

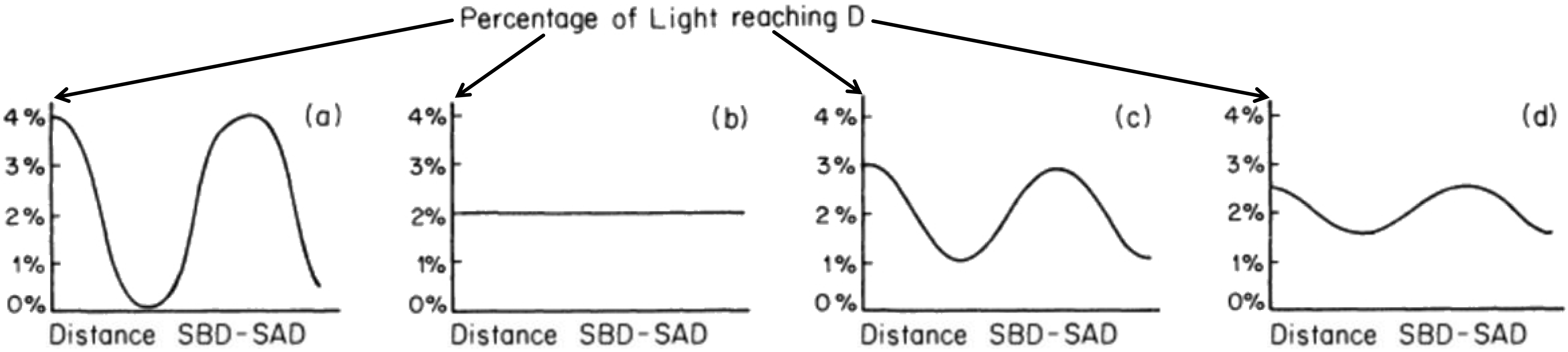


FIGURE 51. When there are no detectors at A or B, there is interference — the amount of light varies from zero to 4% (a). When there are detectors at A and B that are 100% reliable, there is no interference — the amount of light reaching D is a constant 2% (b). When the detectors at A and B are not 100% reliable (i.e., when sometimes there is nothing left in A or in B that can be detected), there are now three possible final conditions — A and D go off, B and D go off, and D goes off alone. The final curve is thus a mixture, made up of contributions from each possible final condition. When the detectors at A and B are less reliable, there is more interference present. Thus, the detectors in case (c) are less reliable than in case (d). The principle regarding interference is: The probability of each of the different possible final conditions must be independently calculated by adding arrows and squaring the length of the final arrow; after that, the several probabilities are added together in the normal fashion.

Part XIII.
Summary: Photons as Clever Explorers

Summary: Photons as Clever Explorers

- Photons behave much like stopwatches moving through space
- Simple graphical addition and multiplication rules explain behavior
- Photon reflection is vastly more flexible than classical reflection
- A single photon reflects from *all* of a mirror, not just the center
- Diffraction gratings prove that photons “see” entire mirror surfaces
- Photons are phenomenally good at finding the fastest paths
- The straight paths of laser pulses do not show how photons move
- Ordinary lenses play almost magical games with probabilities
- Simple “turn and shrink” rules calculate interactions with matter
- Photon interference reaches a maximum when *no* history exists

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