## QED: The Strange Theory of Light and Matter

## Introduction

Many adults are very curious about physics and often ask me for explanations. I generally do all right, but eventually I fail at most interesting point - always get hung up on crazy ideas of quantum mechanics. I can't explain these ideas in an hour or an evening. It requires a much longer time in general.

Over the years I have developed a class for adults that teaches quantum mechanics - some of you have taken that class - presents formal theoretical ideas and requires some math development.
First part of this class going to try, however, following Feynman, to present quantum mechanics in arena of photons and electrons without need for much math development.
Talk first part of physics that known, rather than part that unknown. People always asking for latest developments in unification of this theory with that theory, and don't ever learn about one of theories that know pretty well. - always want to know things that don't know. So, will tell you about subject that very thoroughly analyzed. Will describe as accurately as can strange theory of light and matter - interaction of light and electrons. Called quantum electrodynamics, or QED for short.
Physics has history of synthesizing many phenomena into few theories. For instance, in early days there were phenomena of motion and phenomena of heat; there were phenomena of sound, of light, and of gravity. But soon discovered, after Sir Isaac Newton explained laws of motion, that some of apparently different things were aspects of same thing. For example, phenomena of sound could be completely understood as motion of atoms in air. So sound no longer considered something in addition to motion. Also discovered that heat phenomena easily understandable from laws of motion $->$ large areas of physics theory synthesized into simplified theory. Theory of gravitation, on other hand, not understandable from laws of motion, and even today stands isolated from other theories. Gravitation is, so far, not understandable in terms of other phenomena.
After synthesis of phenomena of motion, sound, and heat, was discovery of number of phenomena that call electrical and magnetic.

In 1873 these phenomena synthesized with phenomena of light and optics into single theory by James clerk Maxwell - proposed light an electromagnetic wave. So at that stage, there were laws of motion, laws of electricity and magnetism, and laws of gravity. Around 1900 theory developed to explain what matter was. Called electron theory of matter, and said were little charged particles inside of atoms. Theory evolved gradually to include heavy nucleus with electrons going around it.

Attempts to understand motion of electrons going around nucleus using mechanical laws - analogous to way Newton used laws of motion to figure out how earth went around sun - were real failure: all predictions came out wrong. Incidentally, theory of relativity - great revolution in physics - was also developed at about that time. But compared to discovery that Newton's laws of motion quite wrong in atoms, theory of relativity was only minor modification. Working out another system to replace Newton's laws took long time because phenomena at atomic level quite strange - had to lose common sense to perceive what happening at atomic level. Finally, in 1926, an "uncommon-sensy" theory developed to explain "new type of behavior" of electrons in matter. Looked cockeyed, but was not: called theory of quantum mechanics. Word 'quantum' refers to peculiar aspect of nature that goes against common sense. This aspect that is subject of this discussion.

Theory of quantum mechanics also explained details, - why oxygen atom combines with 2 hydrogen atoms to make water, and so on. Quantum mechanics supplied theory behind chemistry. So, fundamental theoretical chemistry is really physics.
Because theory of quantum mechanics could explain all chemistry and various properties of substances, was tremendous success. But still existed problem of interaction of light and matter - Maxwell's theory of electricity and magnetism had to be changed to work with new principles of quantum mechanics. So new theory, quantum theory of interaction of light and matter, called by horrible name "quantum electrodynamics", finally developed by physicists in 1929.

But theory troubled. If calculated something roughly, gives reasonable answer.

But if tried compute more accurately - correction thought going to be small was very large - in fact, was infinity! So turned out couldn't really compute anything beyond certain accuracy.
Paul Dirac, using theory of relativity, made relativistic theory of electron - did not completely take into account all effects of electron's interaction with light. Dirac's theory said electron had magnetic moment - something like force of little magnet - that had strength of exactly 1 in certain units. Then in 1948 was discovered in experiments that actual number was closer to 1.00118 (with uncertainty of 3 on last digit). Was known that electrons interact with light, so some small correction expected. Also expected that correction would be understandable from new theory of quantum electrodynamics. But when was calculated, instead of 1.00118 result was infinity - which is wrong, experimentally!
Problem of how to calculate things in quantum electrodynamics straightened out by Julian Schwinger, Sin-Itiro Tomonaga, and Feynman in 1948. Schwinger was first to calculate this correction using new "shell game"; his theoretical value was $1.00116->$ close enough to experimental number to show that were on right track. At last, had quantum theory of electricity and magnetism with which could calculate! This is theory going to describe.
Theory has been put through wringer - some recent numbers: experiments have Dirac's number at 1.00115965221 (with uncertainty of 4 in last digit); theory says 1.00115965246 (with uncertainty of about five times as much). Accuracy of numbers - if measure distance from Los Angeles to New York to this accuracy, would be exact to thickness of human hair. That's how delicately quantum electrodynamics has, in past 50 years, been checked - both theoretically and experimentally. There are other things in quantum electrodynamics that have been measured with comparable accuracy, which also agree very well. Things have been checked at distance scales that range from one hundred times size of earth down to $1 / 100$ size of atomic nucleus. These numbers meant to make you believe theory probably not too far off! Before through, describe how calculations are made.

Impress you with vast range of phenomena that theory of quantum electrodynamics describes:

Easier to say it backwards: theory describes all phenomena of physical world except gravitational effect, thing that holds you in your seats (actually, that's combination of gravity and politeness), and radioactive phenomena, which involve nuclei shifting in their energy levels. So if leave out gravity and radioactivity (nuclear physics), what is left? Gasoline burning in automobiles, foam and bubbles, hardness of salt or copper, stiffness of steel. In fact, biologists are trying to interpret as much as can about life in terms of chemistry, and as already explained, theory behind chemistry is quantum electrodynamics.

Clarify something: When say that all phenomena of physical world can be explained by theory, don't really know that. Most phenomena familiar with involve such tremendous numbers of electrons that hard to follow that complexity. In such situations, can use the theory to figure roughly what ought to happen and that is what happens, roughly, in those circumstances. But if arrange in laboratory experiment involving just few electrons in simple circumstances, then can calculate what might happen very accurately, and can measure very accurately, too. Whenever do such experiments, theory of quantum electrodynamics works very well.

Physicists always checking to see if something the matter with theory. That's the game, because if something wrong, it's interesting! But so far, have found nothing wrong with theory of quantum electrodynamics - jewel of physics - proudest possession.

Theory of quantum electrodynamics also prototype for new theories that attempt to explain nuclear phenomena, things that go on inside nuclei of atoms. If think of physical world as stage, then actors would be not only electrons, which are outside nucleus in atoms, but also quarks and gluons and so forth - dozens of kinds of particles - inside nucleus. And though "actors" appear quite different from one another, all act in certain style - strange and peculiar style - "quantum" style. Will deal with particle physics later. In meantime, going to tell you about photons - particles of light - and electrons, to keep it simple. Because it's way they act that is important, and way they act very interesting.

Now know what lectures about - will you understand it?
Teach physics students in 3rd/4th year of graduate school. No, not going to understand it. Why, doing this? Why are you here when won't understand stuff? I say do not turn away because don't understand stuff - physics students don't understand it either - I don't understand it - Nobody does.

What is meant by "understanding"?. When have lecture, many reasons why might not understand speaker - language bad - doesn't say what means to say, or says it upside down - and hard to understand. That's rather trivial matter, and that will not be a problem in this class.

Another possibility, especially if lecturer is physicist, is that uses ordinary words in funny way. Physicists often use ordinary words such as "work" or "action" or "energy" or even, as you shall see, "light" for some technical purpose. Thus, when I talk about "work" in physics, I don't mean same thing as when I talk about "work" on street. During lecture might use one of those words without noticing that being used in unusual way - try my best to catch myself - that's my job - but is error easy to make.

Next reason that might not understand what I am telling you is, while am describing how Nature works, won't understand why Nature works that way. But you see, nobody understands that. Can't explain why Nature behaves in peculiar ways.

Finally, is this possibility: after tell you something, just can't believe it - can't accept it - don't like it. Little screen comes down and don't listen anymore. Going to describe how Nature is - and if don't like it - going to get in way of your understanding it. Problem that physicists learned to deal with: learned to realize that whether like a theory or don't like theory is not essential question. It is, whether or not theory gives predictions that agree with experiment. It is not question of whether theory philosophically delightful, or easy to understand, or perfectly reasonable from point of view of common sense. Theory of quantum electrodynamics describes Nature as absurd from point of view of common sense. And agrees fully with experiment. So hope can accept Nature as She is - absurd.

Going to have fun talking about absurdity, becausefind it delightful. Please don't turn off because can't believe Nature so strange. Just hear all out, and I hope you'll be as delighted as I am when we're through.
How going to explain things don't explain to students until 3rd-year graduate students? Analogy. Maya Indians interested in rising and setting of Venus as morning "star" and as evening "star" - were very interested in when would appear. After years of observation, noted that 5 cycles of Venus very nearly equal to 8 of "nominal years" of 365 days (were aware that true year of seasons was different and made calculations of that also). To make calculations, Maya invented system of bars and dots to represent numbers (including zero), and had rules by which to calculate and predict not only risings and settings of Venus, but other celestial phenomena, such as lunar eclipses.
In those days, only few Maya priests could do such elaborate calculations. Now, suppose were to ask one of them how to do just one step in process of predicting when Venus will next rise as morning star subtracting two numbers. And let's assume that, unlike today, had not gone to school and did not know how to subtract. How would priest explain to us what subtraction is?
Could either teach us numbers represented by bars and dots and rules for "subtracting" them, or could tell us what was really doing: "Suppose want to subtract 236 from 584 . 1st, count out 584 beans and put in pot. Then take out 236 beans and put to one side. Finally, count beans left in pot - number is result of subtracting 236 from 584".

Might say, "My Quetzalcoatl! What tedium - counting beans, putting them in, taking them out - what a job!"

To which priest would reply, "That's why have rules for bars and dots. Rules tricky, but are much more efficient way of getting answer than counting beans. Important thing - makes no difference as far as answer concerned: can predict appearance of Venus by counting beans (slow, easy to understand) or by using tricky rules (much faster, but must spend years in school to learn them)".

To understand how subtraction works - as long as don't have to actually carry out - not so difficult. That's my position: I'm going to explain what physicists doing when are predicting how Nature will behave, but not going to teach you any tricks so can do it efficiently. Will discover that in order to make any reasonable predictions with new scheme of quantum electrodynamics, would have to make awful lot of little arrows on piece of paper. Takes 7 years - 4 undergraduate and 3 graduate - to train physics students to do that in tricky, efficient way. That's how skip seven years of education in physics: By explaining quantum electrodynamics to you in terms of what really doing, I hope will be able to understand it better than do some of students!

Taking example of Maya one step further, could ask priest why 5 cycles of Venus nearly $=2,920$ days, or 8 years. Would be all kinds of theories about why, such as, " 20 is an important number in our counting system, and if you divide 2,920 by 20 , you get 146 , which is one more than a number that can be represented by the sum of two squares in two different ways", and so forth. But that theory would have nothing to do with Venus, really. In modern times, have found that theories of this kind not useful. So again, not going to deal with Nature behaves in peculiar way She does; no good theories to explain that.
What have done so far is get you into right mood to listen to me. Otherwise, have no chance. So now we're off, ready to go!

Begin with light. When Newton started looking at light, 1 st thing found was that white light is mixture of colors. Separated white light with prism into various colors, but when put light of one color - red, for instance - through another prism, found could not be separated further. So Newton found that white light is mixture of different colors, each of which is pure in sense that can't be separated further. (In fact, particular color of light can be split one more time in different way, according to so-called "polarization". This aspect of light not vital to understanding character of quantum electrodynamics, so for simplicity will leave it out - at expense of not giving you absolutely complete description of theory. This slight simplification will not remove, any real understanding of what will be talking about. Still, must be careful to mention all of things leave out.)

When say "light", don't mean simply light can see, from red to blue. Turns out that visible light just part of long scale that's analogous to musical scale in which there are notes higher than can hear and other notes lower than can hear. Scale of light described by numbers - called frequency - and as numbers get higher, light goes from red to blue to violet to ultraviolet. Can't see ultraviolet light, but can affect photographic plates. It's still light - only number different. (Shouldn't be so provincial: what can detect directly with own instrument - eye, isn't only thing in world!) If continue simply to change number, go out into X-rays, gamma rays, and so on. If change the number in other direction, go from blue to red to infrared (heat) waves, then television waves, and radio waves -> all of that is "light". Going to use just red light for most of examples, but theory of quantum electrodynamics extends over entire range described, and is theory behind all these various phenomena.

Newton thought light made up of particles - called them "corpuscles" - and was right (but reasoning that used to come to decision erroneous). Know that light made of particles because we can take very sensitive instrument that makes clicks when light shines on it, and if light gets dimmer, clicks remain just as loud - just fewer of them. Thus light something like raindrops - each little lump of light called a photon - and if light is all one color, all "raindrops" are same size.
Human eye is very good instrument: takes only about 5 or 6 photons to activate nerve cell and send message to brain. If were evolved little further so could see 10 times more sensitively, wouldn't need this discussion - would all have seen very dim light of one color as series of intermittent little flashes of equal intensity.
Might wonder how possible to detect single photon. One instrument that can do this = photomultiplier, and describe briefly how works: When photon hits metal plate A at bottom (Figure below), causes electron to break loose from one of atoms in plate. Free electron strongly attracted to plate B (has positive charge on it) and hits with enough force to break loose 3 or 4 electrons. Each of electrons knocked out of plate $B$ attracted to plate $C$ (also charged), and collision with plate $C$ knocks loose even more electrons.

Process repeated 10 or 12 times, until billions of electrons, enough to make sizable electric current, hit last plate, L. Current amplified by regular amplifier and sent through speaker to make audible clicks. Each time photon of given color hits photomultiplier, click of uniform loudness heard.


> If put whole lot of photomultipliers around and let some very dim light shine in various directions, light goes into one multiplier or another and makes click of full intensity. It is all or nothing: if one photomultiplier goes off at given moment, none of others goes off at same moment (except in rare instance that 2 photons happened to leave light source at same time). There is no splitting of light into "half particles" that go different places.

Want to emphasize that light comes in this form - particles. Very important to know that light behaves like particles, especially for those of you who have gone to school, where you were probably told something about light behaving like waves. I'm telling you way it does behave - like particles.

Might say that it's just photomultiplier that detects light as particles, but no, every instrument that has been designed to be sensitive enough to detect weak light has always ended up discovering same thing: light is made of particles.

Going to assume familiar with properties of light in everyday circumstances - things like, light goes in straight lines; bends when goes into water; when reflected from surface like mirror, angle at which light hits surface equal to angle at which leaves surface; light can be separated into colors; can see beautiful colors on mud puddle when little bit of oil on it; lens focuses light, and so on. Going to use these phenomena that are familiar with in order to illustrate truly strange behavior of light; Going to explain familiar phenomena in terms of theory of quantum electrodynamics. Showed photomultiplier to illustrate essential phenomenon that may not have been familiar with - that light made of particles - but now are familiar with that, too!

Now, all familiar with phenomenon that light partly reflected from some surfaces, such as water. Many are romantic paintings of moonlight reflecting from lake. When look down into water can see what's below surface (especially in daytime), but can also see reflection from surface. Glass another example: if have lamp on in room and looking out through window during daytime, can see things outside through glass as well as dim reflection of lamp in room. So light partially reflected from surface of glass.

Before go on, want you to be aware of simplification going to make that will correct later on: When talk about partial reflection of light by glass, going to pretend that light reflected by only surface of glass. In reality, piece of glass is terrible monster of complexity - huge numbers of electrons are jiggling about. When photon comes down, interacts with electrons throughout glass, not just on surface. Photon and electrons do kind of dance, net result of which is same as if photon hit only surface. So make simplification for while. Later on, show you what actually happens inside glass so can understand why result is same.

Now like to describe experiment, and tell its surprising results. In this experiment some photons of same color - red light - emitted from light source (Figure below) down toward block of glass.

Photomultiplier placed at A, above glass, to catch any photons reflected by front
 surface. To measure how many photons get past front surface, another photomultiplier placed at $B$, inside glass. Never mind obvious difficulties of putting photomultiplier inside block of glass; what are results of experiment?

For every 100 photons that go straight down toward glass at $90^{\circ}$, average of 4 arrive at A and 96 arrive at B. So "partial reflection" means that $4 \%$ of photons reflected by front surface of glass, while other $96 \%$ transmitted. Already are in great difficulty: how can light be partly reflected? Each photon ends up at A or B how does photon "make up its mind" whether should go to A or B? May sound like joke, but can't just laugh; going to have to explain in terms of theory! Partial reflection already deep mystery, and was very difficult problem for Newton.

Are several possible theories that could make up to account for partial reflection of light by glass. One of them is that $96 \%$ of surface of glass is "holes" that let light through, while other $4 \%$ of surface is covered by small "spots" of reflective material (Figure below).


GLASS Newton realized not possible explanation(see text). Soon will encounter strange feature of partial reflection that will drive you crazy if try to stick to theory of "holes and spots" - or to any other reasonable theory!

Another possible theory is that photons have some kind of internal mechanism - "wheels" and "gears" inside turning in some way - so that when photon "aimed" just right, goes through glass, and when not aimed right, reflects. Can check theory by trying to filter out photons not aimed right by putting few extra layers of glass between source and first layer of glass. After going through filters, photons reaching glass should all be aimed right, and none should reflect. Trouble with theory is, doesn't agree with experiment: even after going through many layers of glass, $4 \%$ of photons reaching given surface reflect off it.

Try to invent reasonable theory that can explain how photon "makes up its mind" whether to go through glass or bounce back, impossible to predict which way given photon will go. Philosophers have said that if same circumstances don't always produce same results, predictions impossible and science will collapse. Here is circumstance - identical photons are always coming down in same direction to same piece of glass - that produces different results. Cannot predict whether given photon will arrive at A or B. All can predict is that out of 100 photons that come down, average of 4 will be reflected by front surface. Does this mean that physics, science of great exactitude, reduced to calculating only probability of an event, and not predicting exactly what will happen? Yes -> a retreat, but that's way it is: Nature permits us to calculate only probabilities. Yet science has not collapsed.

While partial reflection by single surface is deep mystery and difficult problem, partial reflection by two or more surfaces absolutely mind-boggling. Let me show you why.

Do 2nd experiment, measure partial reflection of light by two surfaces. Replace block of glass with very thin sheet of glass - two surfaces exactly parallel to each other - and place photomultiplier below sheet of glass, in line with light source. Photons can reflect from either front surface or back surface to end up at $A$; all others will end up at $B$ (Figure below).


Might expect front surface to reflect 4\% of light and back surface to reflect $4 \%$ of remaining $96 \%$, making total of about $8 \%$. So should find that out of every 100 photons that leave light source, about 8 arrive at A.

What actually happens under these carefully controlled experimental conditions is, number of photons arriving at A rarely 8 out of 100 . With some sheets of glass, consistently get reading of 15 or 16 photons - twice expected result!

With other sheets of glass, consistently get only 1 or 2 photons. Other sheets of glass have partial reflection of $10 \%$; some eliminate partial reflection altogether! What can account for crazy results? After checking various sheets of glass for quality and uniformity, discover differ only slightly in thickness.

To test idea that amount of light reflected by 2 surfaces depends on thickness of glass, do series of experiments: Starting out with thinnest possible layer of glass, count how many photons hit photomultiplier at A each time 100 photons leave light source. Then replace layer of glass with slightly thicker one and make new counts. After repeating process few dozen times, what are results?
With thinnest possible layer of glass, find number of photons arriving at A nearly always 0 - sometimes 1. When replace thinnest layer with slightly thicker one, find amount of light reflected higher - closer to expected $8 \%$. After few more replacements count of photons arriving at A increases past $8 \%$ mark. As continue to substitute still "thicker" layers of glass - up to about 5 millionths of inch now - amount of light reflected by 2 surfaces reaches maximum of $16 \%$, and then goes down, through $8 \%$, back to 0 - if layer of glass just right thickness, there is no reflection at all. (Do that with spots!)

With gradually thicker and thicker layers of glass, partial reflection again increases to $16 \%$ and returns to 0 - cycle that repeats itself again and again (Figure below).


Newton discovered these oscillations and did experiment that could be correctly interpreted only if oscillations continued for at least 34,000 cycles! Today, with lasers (which produce very pure, monochromatic light), can see this cycle still going strong after more than $100,000,000$ repetitions - which corresponds to glass
more than 50 meters thick. (don't see phenomenon every day because light source normally not monochromatic.)
Turns out that prediction of $8 \%$ right as overall average (since actual amount varies in regular pattern from 0 to $16 \%$ ), but exactly right only twice each cycle - like stopped clock (which is right twice a day). How can explain strange feature of partial reflection that depends on thickness of glass? How can front surface reflect $4 \%$ of light (confirmed in 1st experiment) when, by putting 2nd surface at just right distance below, can somehow "turn off" reflection? And placing 2nd surface at slightly different depth, can "amplify" reflection up to $16 \%$ ! Can it be that back surface exerts some kind of influence or effect on ability of front surface to reflect light? What if put in 3rd surface?

With 3rd surface, or any number of subsequent surfaces, amount of partial reflection again changed. Find ourselves chasing down through surface after surface with this theory, wondering if have finally reached last surface. Does photon have to do that in order to "decide" whether to reflect off front surface? Newton made ingenious arguments concerning problem(see text), but realized, in end, that had not developed satisfactory theory.
For many years after Newton, partial reflection by 2 surfaces happily explained by theory of waves(constructive/destructive interference - see text), but when experiments made with very weak light hitting photomultipliers, wave theory collapsed: as light got dimmer and dimmer, photomultipliers kept making full-sized clicks - just fewer of them. Light behaved as particles.

Situation today - haven't got good model to explain partial reflection by 2 surfaces; just calculate probability that particular photomultiplier will be hit by photon reflected from sheet of glass. Chosen this calculation as 1st example of method provided by theory of quantum electrodynamics. Going to show "how we count the beans" - what physicists do to get right answer. Not going to explain how photons actually "decide" whether to bounce back or go through - not known. (Probably question has no meaning.) Will only show how to calculate correct probability that light will be reflected from glass of given thickness, because only thing physicists know how to do! What we do to get answer to problem analogous to things have to do to get answer to every other problem explained by quantum electrodynamics.

Have to brace yourselves for this - not because difficult to understand, but because is absolutely ridiculous: All we do is draw little arrows on piece of paper - that's all! Now, what does arrow have to do with chance that particular event will happen? According to rules of "how we count the beans", probability of event $=$ square of length of arrow. For example, in 1st experiment (when measuring partial reflection by front surface only), probability that photon would arrive at photomultiplier at A was $4 \%$. That corresponds to arrow whose length is 0.2 , because 0.2 squared is 0.04 (Figure below).


In 2nd experiment (when replacing thin sheets of glass with slightly thicker ones), photons bouncing off either front surface or back surface arrived at A. How draw arrow to represent this situation?

Length of arrow must range from 0 to 0.4 to represent probabilities of 0 to $16 \%$, depending on thickness of glass (Figure right).

Start by considering various ways that photon could get from source to photomultiplier at A.


Since making simplification that light bounces off either front surface or back surface $->2$ possible ways photon could get to A. In this case draw 2 arrows - one for each way event can happen - and then combine them into "final arrow" whose square represents probability of event. If had been 3 different ways event could have happened, would have drawn 3 separate arrows before combining them.

Now, show how combine arrows. Say want to combine arrow x with arrow y (Figure below).
All have to do is put head of $x$ against tail of $y$ (without changing
 directions), and draw final arrow from tail of $x$ to head of $y$. That's all there is to it. Can combine any number of arrows in this manner (technically, called "adding arrows"). Each arrow tells you how far, and in what direction, to move in dance. Final arrow tells you what single move to make to end up in same place (Figure below).

Now, what are specific rules that determine length and direction of each arrow that combine in order to make final arrow? In this case, will be combining two arrows - one representing reflection from front surface of glass, and other representing reflection from back surface.

Take length first. As saw in 1st experiment (where put photomultiplier inside glass), front surface reflects about $4 \%$ of photons that come down. Means "front reflection" arrow has length of 0.2. Back surface of glass also reflects 4\%, so "back reflection" arrow's length also 0.2.

To determine direction of each arrow, imagine have stopwatch that can time photon as moves. Imaginary stopwatch has single hand that turns around very, very rapidly. When photon leaves source, start stopwatch. As long as photon moves, stopwatch hand turns (about 36,000 times per inch for red light); when photon ends up at photo-multiplier, stop watch. Hand ends up pointing in certain direction -> direction will draw arrow.

Need one more rule in order to compute answer correctly: When considering path of photon bouncing off front surface of glass, reverse direction of arrow, i.e., draw back reflection arrow pointing in same direction as stopwatch hand but draw front reflection arrow in opposite direction(what is different?).

Now, draw the arrows for case of light reflecting from extremely thin layer of glass. To draw front reflection arrow, imagine photon leaving light source (stopwatch hand starts turning), bouncing off front surface, and arriving at A (stopwatch hand stops). Draw little arrow of length 0.2 in direction opposite that of stopwatch hand (Figure below).


To draw back reflection arrow, imagine photon leaving light source (stopwatch hand starts turning), going though front surface and bouncing off back surface, and arriving at A (stopwatch hand stops). Stopwatch hand is pointing in almost same direction, because photon bouncing off back surface of glass takes only slightly longer to get to A - goes through extremely thin layer of glass twice. Now draw little arrow of length 0.2 in same direction that stopwatch hand is pointing (Figure below).
Now combine 2 arrows. Since both same length but pointing in opposite directions, final arrow has length of nearly 0 , and square even closer to 0 . Thus, probability of light reflecting from and infinitesimally thin layer of glass is essentially 0 (Figure below).



When replace thinnest layer of glass with slightly thicker one, photon bouncing off back surface takes bit longer to get to A than in 1st example; stopwatch hand therefore turns little bit more before stops, and back reflection arrow ends up in slightly greater angle relative to front reflection arrow. Final arrow is little bit longer, and square is correspondingly larger (Figure below).


Another example, look at case where glass just thick enough that stopwatch makes extra half turn as times photon bouncing off back surface. This time, back reflection arrow ends up pointing exactly in same direction as front reflection arrow. When combine 2 arrows, get final arrow whose length is 0.4 , and whose square is 0.16 , representing probability of $16 \%$ (Figure below).

If increase thickness just enough so that stopwatch hand timing back surface path makes extra full turn, 2 arrows end up pointing in opposite directions again, and final arrow will be 0 (Figure below).


If thickness of glass just enough to let stopwatch hand timing back reflection make an extra $1 / 4$ or $3 / 4$ turn, 2 arrows will end up at right angles. Final arrow $=$ hypotenuse of right triangle, and according to Pythagoras, square on hypotenuse $=$ sum of squares of other two sides. Here is value that is right "twice a day" $: 4 \%+4 \%$ makes $8 \%$ (Figure right).


Notice as gradually increase thickness of glass, front reflection arrow always points in same direction, whereas back reflection arrow gradually changes its direction. Change in relative direction of 2 arrows makes final arrow go through repeating cycle of length 0 to 0.4 ; thus square of final arrow goes through repeating cycle of 0 to $16 \%$ that observed in experiments (Figure below).


Just shown how strange feature of partial reflection can be accurately calculated by drawing some little arrows on piece of paper. Technical word for arrows is "probability amplitudes", and feel more dignified when say are "computing the probability amplitude for an event". Prefer, though, to be more honest, and say that are trying to find arrow whose square represents probability of something happening.

Before discussing photons, discuss colors see on soap bubbles. Or better, if car leaks oil in mud puddle, when look at brownish oil in dirty mud puddle, see beautiful colors on surface. Thin film of oil floating on mud puddle something like very thin sheet of glass - reflects light of one color from 0 to maximum, depending on thickness. If shine pure red light on film of oil, see splotches of red light separated by narrow bands of black
(where no reflection) because oil film's thickness not exactly uniform. If shine pure blue light on oil film, see splotches of blue light separated by narrow bands of black. If shine both red and blue light onto oil, see areas that have just right thickness to strongly reflect only red light, other areas of right thickness to reflect only blue light; still other areas have thickness that strongly reflect both red and blue light (see as violet), while other areas have exact thickness to cancel out all reflection, and appear black.

To understand better, need to know that cycle of 0 to $16 \%$ partial reflection by 2 surfaces repeats more quickly for blue light than for red light. Thus at certain thicknesses, one or other or both colors are strongly reflected, while at other thicknesses, reflection of both colors is cancelled out (Figure below).


When shine red and blue light on film of oil, patterns of red and blue, and violet appear, separated by borders of black. When sunlight, which contains red, yellow, green, and blue light, shines on film of oil, areas that strongly reflect each color overlap and produce all kinds of combinations which our eyes see as different colors (see image right).

Cycles of reflection repeat at different rates because stopwatch hand turns faster when times blue photon than does when timing red photon. In fact, that's only difference between red photon and blue photon (or photon of any other color, including radio wave, X-rays, and so on) - speed of stopwatch hand.


As oil film on puddle spreads out and moves over surface of water, changing its thickness in various locations, patterns of color constantly change. (If, on other hand, were to look at same mud puddle at night with one of those sodium streetlights shining on it, would see only yellowish bands separated by black - because those particular streetlights emit light of only one color.)

Phenomenon of colors produced by partial reflection of white light by 2 surfaces called iridescence found in many places. Perhaps have wondered how brilliant colors of hummingbirds and peacocks are produced. Now you know. How those brilliant colors evolved also interesting question. When admire a peacock, should give credit to generations of lackluster females for being selective about their mates. (Man got into act later and streamlined selection process in peacocks.)

In discussion will show how absurd process of combining little arrow computes right answer for those other phenomena are familiar with: light travels in straight lines; reflects off mirror at same angle that came in ("the angle of incidence is equal to the angle of reflection"); lens focuses light, and so on. New framework will describe everything you know about light.

## Photons: Particles of Light

Are talking about light. 1st important feature about light -> appears to be particles: when very weak monochromatic light (light of one color) hits detector, detector makes equally loud clicks less and less often as light gets dimmer.

Other important feature about light is partial reflection of monochromatic light. Average of $4 \%$ of photons hitting single surface of glass reflected. Already deep mystery, since impossible to predict which photons will bounce back and which will go through. With 2nd surface, results strange: instead of expected reflection of $8 \%$ by 2 surfaces, partial reflection can be amplified as high as $16 \%$ or turned off, depending on thickness of the glass.
Strange phenomenon of partial reflection by 2 surfaces can be explained for intense light by theory of waves, but wave theory cannot explain how detector makes equally loud clicks as light gets dimmer. Quantum electrodynamics "resolves" this wave-particle duality by saying light made of particles (as Newton originally thought), but price of great achievement of science is retreat by physics to position of being able to calculate only probability that photon will hit detector, without offering good model of how it actually happens.

Described how physicists calculate probability that particular event will happen. Draw some arrows on piece of paper according to some rules, which go as follows:

GRAND PRINCIPLE: Probability of event = square of length of arrow called "probability amplitude". Arrow of length $0.4->$ probability of 0.16 , or $16 \%$.
GENERAL RULE for drawing arrows if event can happen in alternative ways: Draw arrow for each way, then combine arrows ("add" them) by hooking head of one to tail of next. A "final arrow" then drawn from tail of

Also some specific rules for drawing arrows in case of partial reflection by glass first to head of last. Final arrow is one whose square gives probability of entire event.
Now show how model of world, - so utterly different from anything you've ever seen before, can explain all simple properties of light that you know: when light reflects off mirror, angle of incidence is equal to angle of reflection; light bends when goes from air into water; light goes in straight lines; light can be focused by lens, and so on. Theory also describes many other properties of light that probably not familiar with. Many other phenomena that will not discuss.However, can guarantee every phenomenon about light that has been observed in detail can be explained by theory of quantum electrodynamics, even though going to describe only simplest and most common phenomena.

Start with mirror, and problem of determining how light reflected from it (Figure below).
At S have source that emits light of one color at very low intensity (use red light again). Source emits one photon at a time. At P, place photomultiplier to detect photons. Let's put at same height as source drawing arrows easier if everything symmetrical. Want to calculate chance that detector will make click after photon has been emitted by source. Since possible that photon could go straight across to detector, place screen at Q to prevent that.

(b)


In this experiment, millions of ways photon could go: could go down to left-hand part of mirror at A or B (for example) and bounce up to detector (Figure right); it could bounce off part where you think it should, at G; or, could go down to righthand part of mirror at K or M and bounce up to detector.

Now, would expect that all light that reaches detector reflects off middle of mirror, because that's place where angle of incidence equals angle of reflection. And seems fairly obvious that parts of mirror near two ends have as much to do with reflection as with price of cheese, right?
Although might think that parts of mirror near two ends have nothing to do with reflection of light that goes from source to detector - what does quantum theory say. Rule: probability that particular event occurs is square of final arrow that found by drawing arrow for each way event could happen, and then combining ("adding") arrows. In experiment measuring partial reflection of light by two surfaces, were 2 ways photon could get from source to detector.


You might think that I'm crazy, because for most of ways said photon could reflect off mirror, angles aren't equal. But I'm not crazy, because that's way light really goes! How can that be?

To make problem easier to understand, suppose that mirror consists of only long strip from left to right just as well that forget for moment, that mirror also sticks out from paper (Figure below).

While are millions of places where light could reflect from strip of mirror, make approximation by temporarily dividing mirror into definite number of little squares, and consider only one path for each square - calculation gets more accurate (but harder to do) as make squares smaller and consider more paths.

Now draw little arrow for each way light could go in this situation. Each little arrow has certain length and certain direction. Consider length first. Might think that arrow draw to represent path that goes to middle of mirror, at G, is by far longest (since seems to be very high probability that any photon that gets to detector must go that way), and arrows for paths at ends of mirror must be very short. No, no; should not make such an arbitrary rule. Right rule - what actually happens - much simpler: photon that reaches detector has nearly equal chance of going on any path, so all little arrows have nearly same length. (are some slight variations in length due to various angles and distances involved, but so minor that ignore them.) So say that each little arrow draw will have arbitrary standard length - make the length very short because there are so many of these arrows representing many ways light could go (Figure below).

Although safe to assume that length of all arrows
$\rightarrow$ nearly the same, directions clearly differ because timing different - remember, direction of particular arrow determined by final position of imaginary stopwatch that times photon as moves along particular path. When photon goes way off to left end of mirror, at A, and then up to detector, clearly takes more time than photon that
 gets to detector by reflecting in middle of mirror, at G (Figure right).

Or, imagine for moment that were in hurry and had to run from source over to mirror and then to detector. Know that certainly isn't good idea to go way over to A and then all way up to detector; would be much faster to touch mirror somewhere in middle.

To help us calculate direction of each arrow, going to draw graph right underneath sketch of mirror (Figure below).


Directly below each place on mirror where light could reflect, going to show, vertically how much time would take if light went that way. More time takes, higher point will be on graph. Starting at left, time takes photon to go on path that reflects at A pretty long, so plot point high up on graph. As move toward center of mirror, time takes for photon to go particular way looking at goes down, so plot each successive point lower than previous one. After pass center of mirror, time takes photon to go on each successive path gets longer and longer, so plot points correspondingly higher and higher. To aid eye, connect points: form symmetrical curve that starts high, goes down, and then goes high again.

Now, what does that mean for direction of little arrows? Direction of particular arrow corresponds to amount of time would take photon to get from source to detector following that particular path. Draw arrow, starting at left. Path A takes most time; its arrow points in some direction (Figure above). Arrow for path B points in different direction because time different. At middle of mirror, arrows F, G, and H point in nearly same direction because times nearly the same. After passing center of mirror, see that each path on right side of mirror corresponds to path on left side of mirror whose time is exactly same (consequence of putting source and detector at same height, and path G exactly in middle). Thus arrow for path J , for example has same direction as arrow for path D .

Now let's add little arrow (Figure above). Starting with arrow A, hook arrows to each other, head to tail. Now if were to take walk using each little arrow as step, wouldn't get very far at beginning, because direction from one step to next so different. But after while arrows begin to point in generally same direction, and make some progress. Finally, near end of walk, direction from one step to next again quite different, so stagger about some more.
All have to do now is draw final arrow. Simply connect tail of 1st arrow to head of last one, and see how much progress made on walk (Figure above). And behold - get sizable final arrow! Theory of quantum electrodynamics predicts that light does, indeed reflect off mirror!
Now investigate. What determines how long final arrow is? Notice number of things. 1st ends of mirror not important: there, little arrows wander around and don't get anywhere. If chopped off ends of mirror parts that instinctively knew was wasting time fiddling around with - would hardly affect length of final arrow.

So where is part of mirror that gives final arrow substantial length? It's part where arrows all pointing in nearly same direction - because time almost same. If look at graph showing time for each path (Figure above), see that time nearly same from one path to next at bottom of curve, where time is least.

To summarize, where time least is also where time for nearby paths nearly same; that's where little arrows point in nearly same direction and add up to substantial length; that's where probability of photon reflecting off mirror determined. And that's why, in approximation, can get away with crude picture of world that says that light only goes where time is least and easy to prove that where time least, angle of incidence $=$ angle of reflection.
So theory of quantum electrodynamics gave right answer - middle of mirror is important part for reflection - but correct result came out at expense of believing that light reflects all over mirror, and having to add bunch of little arrows together whose sole purpose was to cancel out. All that might seem to you to be waste of time - some silly game for mathematicians only. After all, doesn't seem like "real physics" to have something there that only cancels out!

Let's test idea that really is reflection going on all over mirror by doing another experiment. 1st, chop off most of mirror, and leave about $1 / 4$, over on left. Still have a pretty big piece of mirror, but in wrong place. In previous experiment arrows on left side of mirror were pointing in directions very different from one another because of large difference in time between neighboring paths. In this experiment going to make more detailed calculation by taking intervals on that left-hand part of mirror that much closer together - fine enough that there is not much difference in time between neighboring paths (Figure below).


With more detailed picture, see that some of arrows point more or less to right; others point more or less to left. If add all arrows together, have bunch of arrows going around in what is essentially a circle, getting nowhere.

But suppose carefully scrape mirror away in areas whose arrows have bias in one direction - (left) --> only those places whose arrows point generally other way remain (Figure below)

When add up only arrows that point more or less to right, get series of dips and substantial final arrow - according to theory, should now have strong reflection. And indeed do -
 theory correct! Such mirror called a diffraction grating, and works like charm. Isn't it wonderful - can take piece of mirror where you didn't expect any reflection, scrape away part of it, and it reflects!(see text)!
Particular grating just showed was tailor-made for red light. Wouldn't work for blue light; would have to make new grating with cut-away strips spaced closer together because, as said earlier, stopwatch hand turns around faster when times blue photon compared to red photon. So cuts especially designed for "red" rate of turning don't fall in right places for blue light; arrows get kinked up and grating doesn't work very well.

But as matter of accident, happens that if move photomultiplier down to somewhat different angle, grating made for red light now works for blue light. Just lucky accident, consequence of geometry involved (Figure below).


If shine white light down on grating, red light comes out at one place, orange light comes out slightly above it, followed by yellow, green, and blue light - all colors of rainbow. Where there is series of grooves close together, can often see colors for example, when hold phonograph record (or better, CD) under bright light at correct angles.

Perhaps have seen those wonderful silvery signs on cars: when car moves, see very bright colors changing from red to blue. Now know where colors come from: looking at grating - mirror that's been scratched in just right places. Sun is light source, and eyes are detector.

So grating shows that can't ignore parts of mirror that don't seem to be reflecting; if do some clever things to mirror, can demonstrate reality of reflections from all parts of mirror and produce striking optical phenomena.

More importantly, demonstrating reality of reflection from all parts of mirror shows that there is amplitude - an arrow - for every way an event can happen. And in order to calculate correctly probability of event in different circumstances, have to add arrows for every way that event could happen - not just ways think are important ones!
Now, would like to talk about something more familiar than gratings - about light going from air into water. This time, put the photomultiplier under- water - suppose experimenter can arrange that! Source of light is in air at S , and detector is underwater, at D (Figure below).


Turns out that light seems to go slower in water than does in air (explain why later), which makes distance through water more "costly", so to speak, than distance through air. Not hard to figure out which path takes least time: suppose you're lifeguard, sitting at S , and someone drowning, at D (Figure right).

Once again, want to calculate probability that photon will get from light source to detector. To make calculation, should consider all ways light could go. Each way light could go contributes little arrow and, as in previous example, all little arrows have nearly same length. Can again make graph of time takes photon to go on each possible path. Graph will be curve very similar to one made for light reflecting off mirror: starts up high, goes down, and then back up again; most important contributions come from places where arrows point in nearly same direction (where time nearly same from one path to next), which is at bottom of curve. That is also where time is least, so all have to do is find out where time least.


Can run on land faster than can swim in water. Problem is, where do enter water in order to reach drowning victim fastest? Run down to water at A , and swim like hell? Of course not. But running directly toward victim and entering water at J not fastest route, either. While would be foolish for lifeguard to analyze and calculate under circumstances, is computable position at which time minimum: it's compromise between taking direct path, though J, and taking path with least water, though N. And so it is with light - path of least time enters water between J and N , such as L .

Another phenomenon of light that would like to mention briefly is mirage. When driving along road that is very hot, can sometimes see what looks like water on road. What really seeing is sky, and when normally see sky on road, because road has puddles of water on it (partial reflection of light by single surface). But how can you see sky on road when no water there? What need to know is that light goes slower through cooler air than through warmer air, and for mirage to be seen, observer must be in cooler air that is above hot air next to road surface (Figure below).


How is possible to look down and see sky can be understood by finding path of least time. I'll let you play with that one at home - it's fun to think about, and pretty easy to figure out.
In examples showed of light reflecting off mirror and of light going through air and then water, making approximation: for simplicity, drew various ways that light could go as double straight lines - two straight lines that form an angle. But don't have to assume that light goes in straight lines when it is in uniform material like air or water; even that explainable by general principle of quantum theory: probability of event found by adding arrows for all ways event could happen.

Next example, show how, by adding little arrows, can appear that light goes in straight line. Put source and photomultiplier at $S$ and P , respectively (Figure below), and look at all ways light could go - in all sorts of crooked paths - to get from source to detector. Then draw little arrow for each path, and we're learning lesson well!


For each crooked path, such as path A, there's nearby path that's little bit straighter and distinctly shorter - that is, takes much less time. But where paths become nearly straight - at C, for example nearby, straighter path has nearly same time. That's where arrows add up rather cancel out; that's where light goes.
Important to note that single arrow that represents straight-line path, through D (Figure above), not enough to account for probability that
 light gets from source to detector. Nearby, nearly straight paths through C and E , for example - also make important contributions. So light doesn't really travel only in straight line; it "smells" neighboring paths around it, and uses small core of nearby space.
(In same way, mirror has to have enough size to reflect normally: if mirror too small for core of neighboring paths, light scatters in many directions, no matter where vou nut mirror )

Investigate this core of light more closely by putting source at S , photomultiplier at P , and pair of blocks between them to keep paths of light from wandering too far away (Figure right).
Now, put 2nd photo-multiplier at Q , below P , and assume again, for simplicity, that light can get from S to Q only by paths of double straight lines. Now, what happens? When gap between blocks wide enough to allow many neighboring paths to P and to Q , arrows for paths to P add up (because all paths to $P$ take nearly same time), while paths to Q cancel out (because those paths have sizable difference in time). Thus photomultiplier at Q doesn't click.


But as push blocks closer together, at certain point, detector at Q starts clicking! When gap nearly closed and there are only few neighboring paths, arrows to Q also add up, because there is hardly any difference in time between them, either (see Fig. 34).


Of course, both final arrows are small, so not much light either way through such small hole, but detector at Q clicks almost as much as one at P ! So when try to squeeze light too much to make sure it's going in only straight line, refuses to cooperate and begins to spread out(see text).
So idea that light goes in straight line is convenient approximation to describe what happens in world familiar to us; similar to crude approximation that says when light reflects off mirror, angle of incidence $=$ angle of reflection.

Just as were able to do clever trick to make light reflect off mirror at many angles, can do similar trick to get light to go from one point to another in many ways.
1st, simplify situation - draw vertical dashed line (Figure below) between light source and detector (line means nothing; just artificial line) and say that only paths going to look at double straight lines.


Graph that shows time for each path looks same as in case of mirror (drawn sideways, this time): curve starts at A, at top, and then comes in, because paths in middle are shorter and take less time. Finally, curve goes back out again.

Now have some fun. Let's "fool the light", so that all paths take exactly same amount of time.

How can do this? How can make shortest path, through M, take exactly same time as longest path through A?
Well, light goes slower in water than does in air; also goes slower in glass (much easier to handle!). So, if put in just right thickness of glass on shortest path, though M, can make time for that path exactly same as for path through A. Paths next to M, which are just little longer, won't need quite as much glass (Figure below).
 Nearer get to A, less glass have to put in to slow up light. By carefully calculating and putting in just right thickness of glass to compensate for time along each path, can make all times same. When draw arrows for each way light could go, find that have succeed in straightening them all out - and there are, in reality, millions of tiny arrows - so net result is sensationally large, unexpectedly enormous final arrow!
Of course know what am describing; it's focusing lens. By arranging things so that all times equal, can focus light - can make probability very high that light will arrive at particular point, and very low that will arrive anywhere else.

Used these examples to show how theory of quantum electrodynamics, which looks at first like absurd idea with no causality, no mechanism, and nothing real to it, produces effects that familiar with: light bouncing off mirror, light bending when goes from air into water, and light focused by lens. Also produces other effects such as diffraction grating, etc. In fact, theory continues to be successful at explaining every phenomenon of light.

Shown with examples how to calculate probability of event that can happen in alternative ways: draw arrow for each way event can happen, and add arrows. "Adding arrows" means arrows are placed head to tail and "final arrow" is drawn. Square of resulting final arrow represents probability of event.

In order to give fuller flavor of quantum theory, now show you how physicists calculate probability of compound events - events that can be broken down into series of steps, or events that consist of number of things happening independently.
Example of compound event can be demonstrated by modifying 1st experiment - aimed some red photons at single surface of glass to measure partial reflection. Instead of putting photomultiplier at A (Figure below), put in screen with hole in it to let photons that reach point A go through. Then put sheet of glass at B, and place photomultiplier at C. How figure out probability that photon will get from source to C ?



Step1:
$S$ to $A$


Can think of event as sequence of 2 steps. Step 1: photon goes from source to point A , reflecting off single surface of glass. Step 2: photon goes from point A to photomultiplier at C, reflecting off sheet of glass at B. Each step has final arrow - an "amplitude" (use words interchangeably) - that can be calculated according to rules know so far. Amplitude for 1 st step has length of 0.2 (square is 0.04 , probability of reflection by single surface of glass), and turned at some angle - say, 2 o'clock (Figure left).

To calculate amplitude for 2nd step, temporarily put light source at A and aim photons at layer of glass above. Draw arrows for front and back surface reflections and add them - say end up with final arrow with length of 0.3 , and turned toward 5 o'clock.
Now, how do we combine 2 arrows to draw amplitude for entire event? Look at each arrow in new way: as instructions for shrink and turn.

In this example, 1st amplitude has length of 0.2 and turned toward 2 o'clock. If begin with "unit arrow" arrow of length 1 pointed straight up - can shrink unit arrow from 1 down to 0.2 , and turn from 12 o'clock to 2 o'clock. Amplitude for 2nd step can be thought of as shrinking unit arrow from 1 to 0.3 and turning from 12 o'clock to 5 o'clock.

Now, to combine amplitudes for both steps, shrink and turn in succession. First, shrink unit arrow from 1 to 0.2 and turn from 12 o'clock to 2 o'clock; then shrink arrow further, from 0.2 down to $3 / 10$ of that, and turn by amount from 12 to 5 - that is, turn from 2 o'clock to 7 o'clock. Resulting arrow has length of 0.06 and pointed toward 7 o'clock. It represents probability of 0.06 squared, or $0.0036=0.36 \%$.

Observing arrows carefully, see that result of shrinking and turning 2 arrows in succession is same as adding their angles ( 2 o'clock +5 o'clock) and multiplying their lengths $(0.2 * 0.3)$. To understand why add angles is easy: angle of arrow determined by amount of turning by imaginary stopwatch hand. So total amount of turning for 2 steps in succession simply sum of turning for 1 st step plus additional turning for 2 nd step.
Why call process "multiplying arrows" takes bit more explanation, but it's interesting. Look at multiplication, for moment, from point of view of Greeks (digression). Greeks wanted to use numbers that were not necessarily integers, so represented numbers with lines. Any number can be expressed as transformation of unit line - by expanding or shrinking it. For example, if line A is unit line (Figure below), line B represents line 2 and line C represents 3 .


Now how multiply 3 times 2? Apply transformations in succession: starting with line A as unit line, expand it 2 times and then 3 times (or 3 times and then 2 times - order doesn't make any difference). Result is line D , whose length represents 6 . What about multiplying $1 / 3$ times $1 / 2$ ? Taking line D to be unit line, now, shrink it to $1 / 2$ (line C) and then to $1 / 3$ of that.

Result is line A , which represents $1 / 6$. Multiplying arrows works same way (Figure below).


Apply transformations to unit arrow in succession - just happens that transformation of arrow involves 2 operations, shrink and turn. To multiply arrow V time arrow W , shrink and turn unit arrow by prescribed amounts for V , and then shrink it and turn it amounts prescribed for W - again, order doesn't make any difference. So multiplying arrows follows same rule of successive transformation that work for regular numbers(see text for more).

Go back to 1st experiment from first lecture - partial reflection by single surface - with this idea of successive steps in mind (Figure below).


Can divide path of reflection into 3 steps: 1) light goes from source down to glass, 2 ) is reflected by glass, and 3) goes from glass up to detector. Each step can be considered as certain amount of shrinking and turning of unit arrow.
You'll remember that earlier, did not consider all ways light could reflect off glass, which requires drawing and adding lots of little tiny arrows. In order to avoid all detail, gave impression that light goes down to particular point on surface of glass that doesn't spread out. When light goes from one point to another, does, in reality, spread out (unless fooled by lens), and there is some shrinkage of unit arrow associated with that. For moment, however, would like to stick to simplified view that light does not spread out, and so is appropriate to disregard shrinkage. Also appropriate to assume that since light doesn't spread out, every photon that leaves source ends up at either A or B.

So: in 1st step no shrinking, but is turning - corresponds to amount of turning by imaginary stopwatch hand as times photon going from source to front surface of glass. In this example, arrow for 1st step ends up with length of 1 at some angle - say 5 o'clock.

2nd step is reflection of photon by glass. Here, is sizable shrink - from 1 to 0.2 - and half turn. (numbers seem arbitrary now: depend upon whether light reflected by glass or some other material. Later, explain them). Thus 2nd step represented by amplitude of length 0.2 and direction of 6 o'clock (half a turn).

Last step is photon going from glass up to detector. Here, as in 1st step, no shrinking, but is turning - say distance slightly shorter than step 1 , and arrow points toward 4 o'clock.

Now "multiply" arrows 1,2, and 3 in succession (add three angles, and multiply lengths). Net effect of 3 steps -1) turning, 2) shrink and half turn, and 3) turning - is same as earlier: turning from steps 1 and $3-$ ( 5 o'clock plus 4 o'clock) is same amount of turning got when let stopwatch run for whole distance ( 9 o'clock); extra half turn from step 2 makes arrow point in direction opposite stopwatch hand, as did earlier, and shrinking to 0.2 in 2 nd step leaves arrow whose square represents $4 \%$ partial reflection observed for single surface.
In experiment, is question didn't look at earlier: what about photons that go to $B$ - ones that are transmitted by surface of glass? Amplitude for photon to arrive at B must have length near 0.98 , since $0.98 * 0.98=0.9604$, which is close enough to $96 \%$. This amplitude can also be analyzed by breaking it down into steps (Figure right).
1st step is same as for path to A - photon goes from light source down to glass - unit arrow is turned toward 5 o'clock.

2nd step is photon passing through surface of glass: there is no turning associated with transmission, just
 bit of shrinking - to 0.98 .

3rd step - photon going through interior of glass - involves no additional turning and no shrinking.
Net result is arrow of length 0.98 turned in some direction, whose square represents probability that photon will arrive at B-96\%.

Now look at partial reflection by 2 surfaces again. Reflection from front surface is same as for single surface, so 3 steps for front surface reflection are same as saw moment ago.



Reflection from back surface can be broken down into 7 steps (Figure right).
Involves turning equal to total amount of turning of stopwatch hand timing photon over entire distance (steps $1,3,5$, and 7 ), shrinking to 0.2 (step 4 ) and two shrinks to 0.98 (steps 2 and 6). Resulting arrow ends up in same direction as before, but length is about $0.192(098 * 0.2 * 0.98)$, which approximated as 0.2 earlier.


In summary, here are rules for reflection and transmission of light by glass: 1) reflection from air back to air (off front surface) involves shrink to 0.2 and half turn; 2) reflection from glass back to glass (off back surface) also involves shrink to 0.2 , but no turning; and 3 ) transmission from air to glass or from glass to air involves shrink to 0.98 and no turning in either case.

Perhaps too much of good thing, but cannot resist showing you cute further example of how things work and are analyzed by these rules of successive steps. Move detector to location below glass, and consider something didn't talk about earlier - probability of transmission by two surfaces of glass (Figure below).


Of course you know answer: probability of photon to arrive at B is simply $100 \%$ minus probability to arrive at A , which worked out beforehand. Thus, if found chance to arrive at A is $7 \%$, chance to arrive at B must be $93 \%$. And as chance for A varies from zero through $8 \%$ to $16 \%$ (due to different thicknesses of glass), chance for B changes from $100 \%$ though $92 \%$ to $84 \%$.

That is right answer, but were expecting to calculate all probabilities by squaring a final arrow. How calculate amplitude arrow for transmission by layer of glass, and how does it manage to vary in length so appropriately as to fit with length for A in each case, so probability for A and probability for B always add up to exactly $100 \%$ ? Look into details.

For photon to go from source to detector below glass, at B, 5 steps involved. Let's shrink and turn unit arrows as go along.

1 st 3 steps are same as in previous example: photon goes from source to lass (turning, no shrinking); photon transmitted by front surface (no turning, shrinking to 0.98 ); photon goes through glass (turning, no shrinking).

4th step - photon passes through back surface of glass - is same as 2 nd step, as far as shrinks and turns go: no turns, but shrinkage to 0.98 of 0.98 , so arrow now has length of 0.96 .

Finally, photon goes through air again, down to detector - means more turning, but no further shrinking. Result is arrow of length 0.96 , pointing in some direction determined by successive turnings of stopwatch hand.
An arrow whose length is 0.96 represents probability of $92 \%$ ( 0.96 squared), which means average of 92 photons reach B out of every 100 that leave source. Also means that $8 \%$ of photons reflected by 2 surfaces and reach A. But found out earlier that $8 \%$ reflection by 2 surfaces only right sometimes ("twice a day") - that in reality, reflection by 2 surfaces fluctuates in cycle from 0 to $16 \%$ as thickness of layer
steadily increases. What happens when glass is just right thickness to make partial reflection of $16 \%$ ? For every 100 photons that leave source, 16 arrive at A and 92 arrive at B, which means $108 \%$ of light has been accounted for - horrifying! Something is wrong.

Neglected to consider all ways light could get to B! For instance, could bounce off back surface, go up through glass as if were going to A , but then reflect off front surface, back down toward B (Figure below).


Path takes 9 steps. Let's see what happens successively to unit arrow as light goes through each step. 1st step - photon goes through air - turning; no shrinking. 2nd step - photon passes through glass - no turning, but shrinking to 0.98 . 3rd step photon goes through glass - turning, no shrinking. 4th step - reflection off back surface - no turning, but shrinking to 0.2 of 0.98 , or 0.196 . 5th step - photon goes back up through glass - turning; no shrinking. 6th step - photon bounces off front surface (really a "back" surface, because photon stays inside glass) - no turning, but shrinking to 0.2 of 0.196 , or 0.0392 . 7th step - photon goes back though glass - more turning; no shrinking. 8th step - photon passes through back surface - no turning, but shrinking to 0.98 of 0.0393 , or 0.0384 . Finally, 9 th step - photon goes through air to detector - turning; no shrinking.

Result of all this shrinking and turning is amplitude of length 0.0384 - call it 0.04 , for practical purposes - and turned at angle that corresponds to total amount of turning by stopwatch as times photon going through longer path. Arrow represents second way that light can get from source to B. Now have two alternatives, so must add 2 arrows - arrow for more direct path, whose length is 0.96 , and arrow for longer way, whose length is 0.04 - to make final arrow.

2 arrows are not usually in same direction, because changing thickness of glass changes relative direction of 0.04 arrow to 0.96 arrow.

But look how nicely things work out: extra turns made by stopwatch timing photon during steps 3 and 5 (on way to A ) are exactly equal to extra turns makes timing photon during steps 5 and 7 (on way to B ). That means when 2 reflection arrows are cancelling each other to make final arrow representing zero reflection, arrows for transmission reinforcing each other to make arrow of length $0.96+0.04$, or $1-$ when probability of reflection is zero, probability of transmission is $100 \%$ (Figure below).


Finally, tell you that there is extension to rule that tells us when to multiply arrows: arrows are to be multiplied not only for an event that consists of a number of things happening concomitantly independently and possibly simultaneously. For example, suppose have 2 sources, X and Y , and 2 detectors, A and B (Figure right), and want to calculate probability for following event: after X and Y each lose a photon, A and B gain a photon.

When arrows for reflection are reinforcing each other to make amplitude of 0.4 , arrows for transmission are going against each other, making amplitude of length 0.96-0.04, or 0.92 - when reflection is calculated to be $16 \%$, transmission is calculated to be $84 \%$ ( 0.92 squared). See how clever Nature is with Her rules to make sure that always come out with $100 \%$ of photons accounted for!(see text for more).


In this example, photons travel through space to get to detectors - they are neither reflected or transmitted - so now is good time for to stop disregarding fact that light spreads out as it goes along. Now present complete rule for monochromatic light travelling from one point to another point through space - nothing approximate here, and no simplification. This is all there is to know about monochromatic light going through space (disregarding polarization): angle of arrow depends on imaginary stopwatch hand, which rotates certain number of times per inch (depending on color of photon); length of arrows inversely proportional to distance light goes - in other words arrow shrinks as light goes along. This rule checks out with what teach in school - amount of light transmitted over distance varies inversely as square of distance - because arrow that shrinks to half its original size has square $1 / 4$ as big.
Suppose arrow for X to A is 0.5 in length and is pointing toward 5 o'clock, as is arrow for Y to B (Figure above). Multiplying one arrow by other, get final arrow of length 0.25 , pointed at 10 o'clock.
But wait! There is another way this event could happen: photon from $X$ could go to $B$, and photon from $Y$ could go to $A$. Each of these subevents has amplitude, and these arrows must be drawn and multiplied to produce an amplitude for this particular way event could happen (Figure right).
Since amount of shrinkage over distance is very small compared to amount of turning, arrows from X to B and Y to A have essentially same length as other arrows, 0.5 , but their turning is quite different: stopwatch hand rotates 36,000 times per inch for red light, so even tiny difference in distance results in substantial difference in timing.
Amplitudes for each way event could happen are added to produce final arrow. Since their lengths are essentially same, is possible for

$X$ to $B$ arrows to cancel each other out if their directions are opposed to each other.

Relative directions of 2 arrows can be changed by changing distance between sources or detectors: simply moving detectors apart or together a little bit can make probability of event amplify or completely cancel out, just as in case of partial reflection by 2 surfaces. This phenomenon, called Hanbury-BrownTwiss effect, has been used to distinguish between single source and double source of radio waves in deep space, even when 2 sources are extremely close together.
In this example, arrows were multiplied and then added to produce final arrow (amplitude for event), whose square is probability of event. Is emphasized that no matter how many arrows draw, add, or multiply, objective is to calculate single final arrow for event. Mistakes often made by physics students at first because do not keep this important point in mind. They work for so long analyzing events involving single photon that begin to think that arrow somehow associated with photon. But these arrows are probability amplitudes, that give, when squared, probability of complete event.
Later will begin process of simplifying and explaining properties of matter - to explain where shrinking to 0.2 comes from, why light appears to go slower through glass or water than through air, and so on because have been cheating so far: photons don't really bounce off surface of glass. Show how photons do nothing but go from one electron to another, and how reflection and transmission are really result of electron picking up photon, "scratching its head", so to speak, and emitting new photon. This simplification of everything have talked about so far is very pretty.

## Electrons and Their Interactions

Continuing discussion on theory of quantum electrodynamics - interaction of light and electrons. Most of phenomena familiar with involve interaction of light and electrons - all of chemistry and biology, for example. Only phenomena not covered by this theory are phenomena of gravitation and nuclear phenomena; everything else contained in this theory
Found out earlier that have no satisfactory mechanism to describe even simplest of phenomena, such as partial reflection of light by glass.

Have no way to predict whether give photon will be reflected or transmitted by glass. All can do is calculate probability that particular event will happen - whether light will be reflected, in this case. (This about $4 \%$, when light shines straight down on single surface of glass; probability of reflection increases as light hits glass at more of a slant.

When deal with probabilities under ordinary circumstances, are following "rules of composition": 1) if something can happen in alternative ways, add probabilities for each of different ways; 2 ) if event occurs as succession of steps - or depends on number of things happening "concomitantly" (independently) then multiply probabilities of each of steps (or things).

In wild and wonderful world of quantum physics, probabilities calculated as square of length of arrow: where would have expected to add probabilities under ordinary circumstances, find ourselves "adding" arrows; where normally would have multiplied probabilities, "multiply" arrows. Peculiar answers that get from calculating probabilities in this manner match perfectly results of experiment. Rather delighted that must resort to such peculiar rules and strange reasoning in order to understand Nature, and enjoy telling people about it. There are no "wheels and gears" beneath analysis of Nature; if want to understand Her, this is what you have to take.

Before proceed with discussion, Show another example of how light behaves. Talk about very weak light of one color - one photon at a time - going from source, at S , to detector, at D (Figure below).

Put screen in between source and detector and make two very tiny holes few millimeters apart from each other, at A and B. (If source
 and detector are 100 centimeters apart, holes have to be smaller than $1 / 10$ of millimeter). Put A in line with S and D , and put B somewhere to side of A , not in line with S and D .

When close hole at $B$, get certain number of clicks at $D$ - which represents photons that came through $A$ (say detector clicks average of one time for every 100 photons that leave S , or $1 \%$ ). When close hole at A and open hole at B , know from earlier that get nearly same number of clicks, on average, because holes are small. (When "squeeze" light too much, rules of ordinary world - such as light goes in straight lines fall apart.) When open both holes get complicated answer, because interference is present: If holes are certain distance apart, get more clicks than expected $2 \%$ (maximum about $4 \%$ ); if two holes are slightly different distance apart, get no clicks at all.

One would normally think that opening 2nd hole would always increase amount of light reaching detector, but that's not what actually happens. And so saying that light goes "either one way or the other" is false. Still catch myself saying, "Well, it either goes this way or that way", but when say that, have to keep in mind that mean in sense of adding amplitudes: photon has an amplitude to go one way. and amplitude to go other way. If amplitudes oppose each other, light won't get there - even though, in case, both holes are open.

Now, here's extra twist to strangeness of Nature to tell you about. Suppose put in some special detectors - one at A and one at B (possible to design detector that can tell whether photon went through it) - so can tell through which hole(s) photon goes through when both holes open (Figure below).

Since probability that single photon will get from $S$ to $D$ affected only
 by distance between holes, must be some sneaky way that photon divides in two and then comes back together again, right? According to hypothesis, detectors at A and B should always go off together (at half strength, perhaps?), while detector at $D$ should go off with probability of from zero to $4 \%$, depending on distance between A and B .

Here's what actually happens: detectors at A and B never go off together - either A or B goes off. Photon does not divide in two; it goes one way or other.

Furthermore, under such conditions detector at D goes off $2 \%$ of time - simple sum of probabilities for A and $\mathrm{B}(1 \%+1 \%) .2 \%$ not affected by spacing between A and B ; interference disappears when detectors are put in at A and B !

Nature has got it cooked up so we'll never be able to figure out how She does it: if put instruments in to find out which way light goes, can find out, all right, but wonderful interference effects disappear. But if don't have instruments that can tell which way light goes, interference effects come back! Very strange, indeed!

To understand paradox, remind you of most important principle: in order to correctly calculate probability of event, one must be very careful to define complete event clearly - in particular, what initial conditions and final conditions of experiment are. Look at equipment before and after experiment, and look for changes. When were calculating probability that photon gets from S to D with no detectors at A or B , event was, simply, detector at D makes click. When click at D was only change in conditions, there was no way to tell which way photon went, so there was interference.
When put in detectors at A and B, changed problem. Now, turns out, are 2 complete events -2 sets of final conditions - that are distinguishable: 1) detectors at A and D go off, or 2 ) detectors at B and D go off. When there are number of possible final conditions in experiment, must calculate probability of each as separate, complete event.

To calculate amplitude that detectors at A and D go off, multiply arrows that represent following steps: photon goes from S to A , photon goes from A to D , and detector at D goes off. Square of final arrow is probability of this event $-1 \%$ - same as when hole at B was closed, because both cases have exactly same steps. Other complete event is detectors at B and D goes off. Probability of this event calculated in similar way, and is also same as before - about $1 \%$.

If want to know how often detector at $D$ goes off and don't care whether was $A$ or $B$ that went off in process, probability is simple sum of two events $-2 \%$.

In principle, if there is something left in system that could have observed to tell which way photon went, have different "final states" (distinguishable final conditions), and add probabilities - not amplitudes - for each final state.
Complete story on this situation very interesting: if detectors at A and B not perfect, and detect photons only some of time, then there are 3 distinguishable final conditions: 1) detectors at A and D go off; 2) detectors at $B$ and $D$ go off, and 3) detector at $D$ goes off alone, with $A$ and $B$ unchanged (left in their initial state).
Probabilities for 1st two events calculated in way explained above (except will be extra step - shrink for probability that detector at A [or B ] goes off, since detectors not perfect). When $D$ goes off alone, can't separate 2 cases, and Nature plays with us by bringing in interference - same peculiar answer would have had if there were no detectors (except that final arrow is shrunk by amplitude that detectors do not go off). Final result is mixture, simple sum of all 3 cases (Figure above). as reliability of detectors increases, get less interference.

I have pointed out these things because more you see how strangely Nature behaves, harder is to make model that explains how even simplest phenomena work. So theoretical physics has given up on that.

We saw earlier how event can be divided into alternative ways and how arrow for each way can be "added". Also saw how each way can be divided into successive steps, how arrow for each step can be regarded as transformation of unit arrow, and how arrows for each step can be "multiplied" by successive shrinks and turns. Thus familiar with all necessary rules for drawing and combining arrows (that represent bits and pieces of events) to obtain final arrow, whose square is probability of an observed physical event.

Is natural to wonder how far can push this process of splitting events into simpler and simpler subevents. What are smallest possible bits and pieces of events? Is there limited number of bits and pieces that can be compounded to form all phenomena that involve light and electrons? Is there limited numbers of "letters" in this language of quantum electrodynamics that can be combined to form "words" and "phrases" that describe nearly every phenomenon of Nature?

Answer is yes; number is 3 . There are only three basic actions needed to produce all of phenomena associated with light and electrons.

Before tell you what 3 basic actions are, should properly introduce you to actors. Actors are photons and electrons. Photons, particles of light, discussed at length earlier. Electrons discovered in 1895 as particles: could count them; could put one of them on oil drop and measure electric charge. Gradually became apparent that motion of these particles accounted for electricity in wires.

Shortly after electrons discovered was thought that atoms were like little solar systems, made up of central, heavy part (called nucleus) and electrons, which went around in "orbits", much like planets do when go around sun. If think that's way atoms are, then back in 1910. In 1924 Louis De Broglie found that there was wavelike character associated with electrons, and soon afterwards, C.J. Davisson and L.H. Germer of Bell Laboratories bombarded nickel crystal with electrons and showed that they, too, bounced off at crazy angles (just like X-rays do), and that these angles could be calculated from De Broglie's formula for wavelength of electron.

When look at photons on large scale - much larger than distance required for one stopwatch turn phenomena that see very well approximated by rules such as "light travels in straight lines", because are enough paths around path of minimum time to reinforce each other, and enough other paths to cancel each other out. But when space through which photon moves becomes too small (such as tiny holes in screen), rules fail - discover that light doesn't have to go in straight lines, there are interferences created by two holes, and so on.

Same situation exists with electrons: when seen on large scale, travel like particles, on definite paths. But on small scale, such as inside an atom, space so small that there is no main path, no "orbit"; there are all sorts of ways electron could go, each with an amplitude. Phenomenon of interference becomes very important, and have to sum arrows to predict where electron is likely to be.

Rather interesting to note that electrons looked like particles at first, and wavish character later discovered. On other hand, apart from Newton making mistake and thinking that light was "corpuscular", light looked like waves at first, and characteristics as particle discovered later. In fact, both objects behave somewhat like waves, and somewhat like waves, and somewhat like particles. In order to save ourselves from inventing new words such as "wavicles", have chosen to call objects "particles", but all know they obey these rules for drawing and combining arrows been explaining. Appears that all "particles" in Nature - quarks, gluons, neutrinos, and so forth (discussed later) - behave in this quantum mechanical way.
So now, present to 3 basic actions, from which all phenomenon of light and electrons arise.

## Action \#1: A photon goes from place to place.

## Action \#2: An electron goes from place to place.

## Action \#3: An electron emits or absorbs a photon.

Each of these actions has an amplitude - and arrow - that can be calculated according to certain rules. In moment, tell you those rules, or laws, out of which can make whole world (aside from nuclei, and gravitation, as always!).

Now, stage on which these actions take place is not just space, it is space and time. Until now, have disregarded problems concerning time, such as exactly when photon leaves source and exactly when arrives at detector. Although space 3-dimensional, going to reduce to 1 dimension on graphs going to draw: Show particular object's location in space on horizontal axis, and time on vertical axis.

1st event going to draw in space and time - or space-time, as might call it is baseball standing still (Figure right).
On Thursday morning, which label as T0, baseball occupies certain space, which label as X0. Few moments later, at T1, occupies same space, because standing still. Few moments later, at T2, baseball still at X0. So diagram of baseball standing still is vertical band, going straight up, with baseball all over it inside.
What happens if have baseball drifting in weightlessness of outer space, going straight toward wall? Well on Thursday morning (T0) starts at X0 (Figure right), but little bit later, not in same place - has drifted over little bit, to X1.

As baseball continues to drift, creates slanted "band of baseball" on diagram in space-time. When baseball hits wall (standing still -> vertical band), goes back other way, exactly where it came from in space (X0), but to different point in time (T6).
As for time scale, most convenient to represent time not in seconds, but in much smaller units. Since will be dealing with photons and electrons, which move very rapidly, going to have $45^{\circ}$ angle represent something going speed of light. For example, for particle moving at speed of light from X 1 T 1 to X 2 T 2 , horizontal distance between X 1 and X 2 is same as vertical distance between T 1 and T 2 (Figure right). Factor by which time stretched out (to make $45^{\circ}$ angle represent particle going speed of light) called c, and find c's flying around everywhere in Einstein's formulas result of unfortunate choice of second as unit of time, rather than time
 takes light to go 1 meter.

Thus time scale will use in graphs will show particles going at speed of light to be travelling at 45-degree angle through space-time. Amount of time takes light to go 30 centimeters - from X1 to X2 or from X2 to X 1 - is about one-billionth of a second.

Now, look at 1 st basic action in detail - photon goes from place to place. Draw action as wiggly line from A to B for no good reason. Should be more careful: should say, photon that is known to be at given place at given time has certain amplitude to get to another place at another time. On space-time graph (Figure right), photon at point A - at X1 and T 1 - has amplitude to appear at point B X 2 and T 2 . Size of this amplitude call $\mathrm{P}(\mathrm{A}$ to B$)$.


There is formula for size of this arrow, $\mathrm{P}(\mathrm{A}$ to B$)$. Is one of great laws of Nature, and very simple. Depends on difference in distance and difference in time between 2 points. These differences expressed mathematically as (X2-X1) and (T2 - T1).
In these lectures, plotting point's location space in 1 dimension, along x -axis. To locate point in 3dimensional space, "room" has to be set up, and distance of point from floor and from each of 2 adjacent walls (all at right angles to each other) has to be measured. 3 measurements labeled $\mathrm{X} 1, \mathrm{Y} 1$ and Z 1 . Actual distance from this point to 2nd point with measurements $\mathrm{X} 2, \mathrm{Y} 2, \mathrm{Z} 2$ calculated using "threedimensional Pythagorean Theorem": square of actual distance is

$$
\left(X_{2}-X_{1}\right)^{2}+\left(Y_{2}-Y_{1}\right)^{2}+\left(Z_{2}-Z_{1}\right)^{2}
$$

Excess of this over time difference, squared -

$$
\left(X_{2}-X_{1}\right)^{2}+\left(Y_{2}-Y_{1}\right)^{2}+\left(Z_{2}-Z_{1}\right)^{2}-\left(T_{2}-T_{1}\right)^{2}
$$

- is sometimes called "the Interval", or I, and is combination that Einstein's theory of relativity says that $\mathrm{P}(\mathrm{A}$ to B$)$ must depend on.

Most of contribution to final arrow for $\mathrm{P}(\mathrm{A}$ to B$)$ is just where would expect it - where difference in distance is equal to difference in time (that is, when I is zero). But in addition; there is contribution when I not zero, that is inversely proportional to I : it points in direction of 3 o'clock when I is more than zero (when light going faster than $c$ ), and points toward 9 o'clock when I is less than zero. These later contributions cancel out in many circumstances (Figure below).


Major contribution to $\mathrm{P}(\mathrm{A}$ to B$)$ occurs at conventional speed of light when ( $\mathrm{X} 2-\mathrm{X} 1$ ) is equal to ( $\mathrm{T} 2-\mathrm{T} 1$ ) - where one would expect it all to occur, but there is also amplitude for light to go faster (or slower) than conventional speed of light. Found out earlier that light doesn't go only in straight lines; now, find out that it doesn't go only at speed of light!

May surprise you that there is amplitude for photon to go at speeds faster or slower than conventional speed, c. Amplitudes for these possibilities very small compared to contribution from speed c; in fact, cancel out when light travels over long distances. However, when distances short - as in many of diagrams will be drawing - other possibilities become vitally important and must be considered.

So that's 1st basic action, 1st basic law of physics - photon goes from point to point. That explains all about optics; that's entire theory of light! Well, not quite: left out polarization (as always), and interaction of light with matter, which brings 2nd law.

2nd action fundamental to quantum electrodynamics is: An electron goes from point A to point B in space-time. (imagine electron as simplified, fake electron, with no polarization - what physicists call "spin-zero" electron. In reality, electrons have type of polarization, which doesn't add anything to main ideas; only complicates formulas little bit.) Formula for amplitude for this action, which call E(A to B) also depends on (X2-X1) and (T2-T1) (in same combination as described before) as well as on number will call " $n$ ", number that, once determined, enables all calculations to agree with experiment. (will see later how we determine n's value.)

Rather complicated formula, and don't know how to explain it in simple terms. However, might be interested to know that formula for $\mathrm{P}(\mathrm{A}$ to B$)$ - a photon going from place to place in space-time - is same as that for $\mathrm{E}(\mathrm{A}$ to B$)$ - an electron going from place to place - if n set to zero.

Formula for E (A to B ) complicated, but there is interesting way to explain what it amounts to. E (A to B) can be represented as giant sum of lot of different ways electron could go from point $A$ to point $B$ in space-time (Figure below): electron could take "one-hop flight", going directly from A to B; could take "two-hop flight", stopping at intermediate point C; could take "three-hop flight", stopping at points D and E , and so on. In such an analysis, amplitude for each "hop" - from one point F to another point Gis $\mathrm{P}(\mathrm{F}$ to G$)$, same as amplitude for photon to go from point F to point G . Amplitude for each "stop" represented by $\mathrm{n}^{2}$, n being same number mentioned before which we is used to make calculations come
out right.
(a)

(b)


Formula for $\mathrm{E}(\mathrm{A}$ to B$)$ is thus series of terms: $\mathrm{P}(\mathrm{A}$ to B$)$ [ "one-hop" flight] + P(A to C)*n 2 * P(C to B) ["two-hop" flights, stopping at C$]+\mathrm{P}(\mathrm{A}$ to D$) * \mathrm{n} 2 * \mathrm{P}(\mathrm{D}$ to E$) * \mathrm{n} 2 * \mathrm{P}(\mathrm{E}$ to B) ["three-hop" flights, stopping at D and E] + ..... for all possible intermediate points $\mathrm{C}, \mathrm{D}, \mathrm{E}$, and so on.

Note that when n increases, nondirect paths make greater contribution to final arrow. When n is zero (as for photon), all terms with an $n$ drop out (because $=$ zero), leaving only first term, which is $\mathrm{P}(\mathrm{A}$ to B$)$. Thus $\mathrm{E}(\mathrm{A}$ to B$)$ and $\mathrm{P}(\mathrm{A}$ to B) are closely related.

3rd basic action is : electron emits or absorbs photon - doesn't make any difference which. Call this action a "junction", or "coupling". To distinguish electrons from photons in my diagrams, will draw each electron going though space-time as straight line. Every coupling, therefore, is junction between two straight lines and wavy line (Figure below).

Time

There is no complicated formula for amplitude of an electron to emit or absorb photon; doesn't depend on anything - just a number! This junction number $=\mathrm{j}-$ value about -0.1 : shrink to about $1 / 10$, and half turn. This number, amplitude to emit or absorb photon = "charge" of particle. Well, that's all there is to these basic actions - except for some slight complications due to polarization that always leaving out. Next job is to put these 3 actions together to represent circumstances that are somewhat more complicated.

For 1st example, calculate probability that 2 electrons, at points 1 and 2 in space-time, end up at points 3 and 4 (Figure below).

 This event can happen in several ways. 1st way is that electron at 1 goes to 3 - computed by putting 1 and 3 into formula E (A to $B$ ), which write $E(1$ to 3$)$ - and electron at 2 goes to 4 computed by $\mathrm{E}(2$ to 4$)$. These are two "subevents" happening concomitantly, so two arrows multiplied to produce arrow for this 1st way event could happen. Therefore write formula for "first way arrow" as $\mathrm{E}(1$ to 3$) * \mathrm{E}(2$ to 4$)$.

Another way event could happen is that electron at 1 goes to 4 and electron at 2 goes to 3 - again, two concomitant subevents."second way arrow" is $\mathrm{E}(1$ to 4$) * \mathrm{E}(2$ to 3$)$, and add it to "first-way" arrow. Had I included effects of polarization of electron, "second-way" arrow would have been "subtracted" - turned $180^{\circ}$ and added (more later).

This is good approximation for amplitude of this event. To make more exact calculation that will agree more closely with results of experiment, must consider other ways this event could happen. For instance, for each of two main ways event can happen, one electron could go charging off to some new and wonderful place and emit photon (Figure below).


Meanwhile, other electron could go to some other place and absorb photon. Calculating amplitude for 1st of these new ways involves multiplying amplitudes for : electron goes from 1 to new and wonderful place, 5 (where emits photon), and then goes from 5 to 2; other electron goes from 2 to other place, 6 (where absorbs photon), and then goes from 6 to 4 .

Must remember to include amplitude that photon goes from 5 to 6 . Going to write amplitude for this way event could happen in high-class mathematical fashion, and you can follow along:

$$
\mathrm{E}(1 \text { to } 5) * \mathrm{j} * \mathrm{E}(5 \text { to } 3) * \mathrm{E}(2 \text { to } 6) * \mathrm{j} * \mathrm{E}(6 \text { to } 4) * \mathrm{P}(5 \text { to } 6)
$$

a lot of shrinking and turning. (you figure out notation for other case, where electron at 1 ends up at 4, and electron at 2 ends up at 3.) Final conditions of experiment for these more complicated ways are same as for simpler ways - electrons start at points 1 and 2 and end up at points 3 an 4 - so cannot distinguish between these alternatives and first two. Therefore we must add arrows for these two ways to two ways just previously considered.

But wait: positions 5 and 6 could be anywhere in space and time - yes, anywhere - and arrows for all of those positions have to be calculated and added together. See it's getting to be lot of work. Not that rules are so difficult - like playing checkers: rules simple, but use them over and over. So difficulty in calculating comes from having to pile so many arrows together. That's why takes 4 years of graduate work for students to learn how to do it efficiently - and looking at easy problem! (when problems get too difficult, just put them on computer!)

I would like to point out something about photons being emitted and absorbed: if point 6 is later than point 5 , might say that photon emitted at 5 and absorbed at 6 (Figure below).


Now, in addition to photon that is exchanged between 5 and 6, another photon could be exchanged - between two points, 7 and 8 (Figure below). Too messy to write down all basic actions whose arrows have to be multiplied, but - as may have noticed - every straight line gets an $E(A$ to $B)$, every wavy line gets a $P(A$ to $B)$, and every coupling gets a $j$. Thus, there are six E(A to B)'s two P(A to B)'s, and four j's - for every possible $5,6,7$, and 8 ! That makes billions of tiny arrows that have to be multiplied and then added together!

If 6 earlier than 5 , might prefer to say photon emitted at 6 and absorbed at 5, but could just as well say that photon going backwards in time! However, don't have to worry about which way in space-time photon went; all included in formula for $\mathrm{P}(5$ to 6), and say photon was "exchanged". Isn't it beautiful how simple Nature us!


Appears that calculating amplitude for simple case is hopeless business, but when you're graduate student you've got to get your degree, so you keep on going.

But there is hope for success. Found in that magic number, j, 1st two ways event could happen has no j's in calculation; next way has $\mathrm{j} * \mathrm{j}$, and last way looked at had $\mathrm{j} * \mathrm{j} * \mathrm{j} * \mathrm{j}$. Since $\mathrm{j} * \mathrm{j}$ is less than 0.01 , it means length of arrow for this way generally less than $1 \%$ of arrow forfirst two ways; and arrow with $\mathrm{j} * \mathrm{j} * \mathrm{j} * \mathrm{j}$ in it less than $1 \%$ of $1 \%$ - one part in 10,000 - compared to arrows that have no $j$. If got enough time on computer, can work out possibilities that involve $\mathrm{j}^{6}$ - one part in a million - and match accuracy of experiments. That's how calculations of simple events are made. That's way it works; that's all there is to it!

Look at another event now. Begin with photon and an electron, and end with photon and an electron. One way for this event to happen is: photon absorbed by electron, electron continues on a bit, and new photon comes out. Process is called scattering of light. When make diagrams and calculations for scattering, must include some peculiar possibilities (Figure below).


For example, electron could emit photon before absorbing one (b). Even more strange is possibility (c) that electron emits photon, then travels backwards in time to absorb photon, and then proceeds forward in time again. Path of such "backwardsmoving" electron can be so long as to appear real in actual experiment in laboratory. Its behavior is included in these diagrams and equations for $\mathrm{E}(\mathrm{A}$ to B$)$.

The backwards-moving electron when viewed with time moving forward appears same as ordinary electron, except it's attracted to normal electrons - say it has "positive charge". (if included effects of polarization, would be apparent why sign of j for backwards-moving electron appears reversed, making charge appear positive,) For this reason called "positron". Positron is sister particle to electron, and is example of an "anti-particle".

Phenomenon is general. Every particle in Nature has amplitude to move backwards in time, and therefore has an anti-particle. When particle and its anti-particle collide, annihilate each other and form other particles. (For positrons and electrons annihilating, usually photon or two.) What about photons? Photons look exactly same in all respects when travel backwards in time - as saw earlier - so are own anti-particles. See how clever we are at making an exception part of the rule! Now show what backwards-moving electron looks like to us, as move forwards in time. With sequence of parallel lines to aid eye, going to divide diagram into blocks of time, T0 to T10 (Figure below).


Start at T0 with electron moving toward photon, which is moving in opposite direction. All of a sudden - at T3 - photon turns into 2 particles, positron and an electron. Positron doesn't last very long: soon runs into an electron - at T5, where annihilate and produce new photon. Meanwhile, electron created earlier by original photon continues on through space-time.

Next thing would like to talk about is an electron in an atom. In order to understand behavior of electrons in atoms, have to add one other
feature, the nucleus - heavy part at center of an atom that contains at least one proton (proton is "Pandora's Box" that will open later). Will not give you correct laws for behavior of nucleus now complicated. But in this case, where nucleus is quiet, can approximate behavior as that of particle with amplitude to go from one place to another in space-time according to formula for $\mathrm{E}(\mathrm{A}$ to B$)$, but with much higher number for $n$. Since nucleus so heavy compared to electron, can deal with approximately by saying that stays in essentially one place as moves through time.

Simplest atom, called hydrogen, is proton and electron. By exchanging photons, proton keeps electron nearby, dancing around it (Figure right). Amplitude for photon exchange is $(-\mathrm{j}) * \mathrm{P}(\mathrm{A}-\mathrm{B}) * \mathrm{j}$ - two couplings and amplitude for photon to go from place to place. Amplitude for proton to have coupling with photon is -j .

Now, show you diagram of an electron in hydrogen atom scattering light (Figure right).

As electron and nucleus exchanging photons, photon comes from outside atom, hits electron and absorbed; then new photon emitted. (As usual, are other possibilities to be considered, such as new photon emitted before old photon is absorbed.) Total amplitude for all ways electron can scatter photon can be summed up as single arrow, certain amount of shrink and
 turn. (Later, call this arrow "S".). Amount depends on nucleus and arrangement of electrons in atoms, and is different for different materials.

Now, look again at partial reflection of light by layer of glass. How does it work? Talked about light being reflected from front surface and back surface. This idea of surfaces was simplification made in order to keep things easy at beginning. Light not really affected by surfaces. An incoming photon is scattered by electrons in atoms inside glass, and new photon comes back up to detector. Interesting that instead of adding up all billions of tiny arrows that represent amplitude for all electrons inside glass to scatter incoming photon, can add just two arrows - for "front surface" and "back surface" reflections and come out with same answer. Let's see why.
To discuss reflection by layer from new point of view must take into account dimension of time.
Previously, when talked about light from monochromatic source, used imaginary stopwatch that times photon as moves - hand of stopwatch determined angle of amplitude for given path. In formula for $\mathrm{P}(\mathrm{A}$ to B) (amplitude for photon to go from point to point) no mention of any timing. What happened to stopwatch? What happened to turning?

Earlier, simply said light source monochromatic. To correctly analyze partial reflection by layer, need to know more about monochromatic light source.

Amplitude for photon to be emitted by source varies, in general, with time: as time goes on, angle of amplitude for photon to be emitted by source changes. Source of white light - many colors mixed together - emits photons in chaotic manner: angle of amplitude changes abruptly and irregularly in fits and starts. But when construct monochromatic source, are making device that has been carefully arranged so that amplitude for photon to be emitted at certain time easily calculated: it changes its angle at constant speed, like stopwatch hand. (Actually, arrow turns at same speed as imaginary stopwatch used before, but in opposite direction - Figure below).

> Rate of turning depends on color of light: amplitude for blue source turns nearly twice as fast as that for red source, just as before. So timer used for "imaginary stopwatch" was monochromatic source: in reality, angle of amplitude for given path depends on what time photon emitted from source,
> Once photon has been emitted, no further turning of arrow as photon goes from one point to another in space-time. Although formula P(A to B) says there is amplitude for light to go from one place to another at speeds other than c, distance from source to detector in our
experiment is relatively large (compared to an atom), so only surviving contribution to $\mathrm{P}(\mathrm{A}$ to B$)$ 's length that counts comes from speed $c$.

To begin new calculation of partial reflection, start by defining event completely: detector at A makes click at certain time, T. Then, divide layer of glass into number of very thin sections - say, six (Figure below).
(a)

(c)

(b)


All right, let's calculate arrows for each of these ways light could go - via six points, X1 to X6. There are four steps involved in each way (which means four arrows will be multiplied):

STEP \#1: A photon is emitted by the source at a certain time.
STEP \#2: The photon goes from the source to one of the points in the glass.
STEP \#3: The photon is scattered by an electron at that point.
STEP \#4: A new photon makes its way up to the detector.

Say amplitudes for steps 2 and 4 (photon goes to or from point in glass) involve no shrinking or turning, because assume that none of light gets lost or spread out between source and glass or between glass and detector. For step 3 (electron scatters photon) amplitude for scattering is constant - a shrink and turn by certain amount, S - and is same everywhere in glass. (amount is, as mentioned before, different for different materials. For glass, turn of $S$ is $90^{\circ}$.) Therefore, of 4 arrows to be multiplied, only arrow of step 1 - amplitude for photon to be emitted from source at certain time - is different from one alternative to next.

Time at which photon would have been emitted to reach detector A at time T (Figure above(b)) is not same for 6 different paths. Photon scattered by X2 would have to have been emitted slightly earlier than photon scattered by X 1 because that path longer. Thus arrow at T 2 is turned slightly more than arrow at T 1 because amplitude for monochromatic source to emit photon at certain time rotates counterclockwise as time goes on. Same goes for each arrow down to T6: all 6 arrows have the same length, but are turned at different angles - that is, pointing in different directions - because represent photon emitted by source at different times.

After shrinking arrow at T1 by amounts prescribed in steps 2,3 and 4 - turning it $90^{\circ}$ prescribed in step 3 - end up with arrow 1 (Figure above(c)). Same goes for arrows 2 through 6 . Thus arrows 1 through 6 are all same (shortened) length, and turned relative to each other in exactly same amount as arrows at T1 through T6.

Next add arrows 1 to 6 . Connecting arrows in order from 1 to 6 , get something like an arc, or part of circle. Final arrow forms chord of arc. Length of final arrow increases with thickness of glass - thicker glass means more sections, more arrows, and therefore more of circle - until half circle is reached (and final arrow is diameter). Then length of final arrow decreases as thickness of glass continues to increase, and circle becomes complete to begin new cycle. Square of this length is probability of event, and varies in cycle of 0 to $16 \%$.

There is mathematical trick can use to get same answer (Figure above(d)): If draw arrows from center of "circle" to tail of arrow 1 and to head of arrow 6 , get two radii. If radius arrow from center to arrow 1 turned $180^{\circ}$ ("subtracted"), then can be combined with other radius arrow to give same final arrow! That's what was doing earlier: these two radii are two arrows said represented "front surface" and "back surface" reflections. Each have famous length of 0.2 (more in text).

Thus can get correct answer for probability of partial reflection by imagining (falsely) that all reflection comes from only front and back surfaces. In intuitively easy analysis, "front surface' and "back surface" arrows are mathematical constructions that give right answer, whereas analysis just did - with space-time drawing and arrows forming part of circle - is more accurate representation of what is really going on: partial reflection is scattering of light by electrons inside glass.

Now, what about light that goes through layer of glas First, is amplitude that photon goes straight through glass without hitting any electrons (Figure right(a)).

This is most important arrow in terms of length. But are 6 other ways photon could reach detector below glass: photon could hit X1 and scatter new photon down to $B$; photon could hit X2 and scatter new photon down to $B$, and so on. These 6 arrows all have same length as arrows that form "circle" in previous example: length based on same amplitude of electron in glass to scatter photon, S. But this time,

all 6 arrows point in same direction, because length of all 6 paths that involve one scattering is same. Direction of these minor arrows is at right angles to main arrow for transparent substances such as glass. When minor arrows are added to main arrow, result in final arrow that has same length as main arrow,
but is turned in slightly different direction. Thicker the glass, more minor arrows there are, and more final arrow turned. That's how focusing lens really works: final arrows for all paths can be made to point in same direction by inserting extra thicknesses of glass into shorter paths.

Same effect would appear if photons went slower through glass than through air: there would extra turning of final arrow. That's why said earlier that light appears to go slower in glass (or water) than through air. In reality, "slowing" of light is extra turning caused by atoms in glass ( or water) scattering light. Degree to which is extra turning of final arrow as light goes through given material called its "index of refraction".

For substances that absorb light, minor arrows are at less than right angles to main arrow (Figure above(b)). This causes final arrow to be shorter than main arrow, indicating that probability of photon going though partially opaque glass smaller than through transparent glass.

Thus all phenomena and arbitrary numbers mentioned earlier - such as partial reflection with amplitude of 0.2 , "slowing" of light in water and glass, and so on - explained in more detail by just 3 basic actions three actions that do, in fact, explain nearly everything else, too.

Hard to believe that nearly all vast apparent variety in Nature results from monotony of repeatedly combining just 3 basic actions. But it does. Outline bit of how some of variety arises.

Start with photons (Figure below).


What is probability that 2 photons, at points 1 and 2 in spacetime, go to 2 detectors, at points 3 and 4 ? Are 2 main ways event could happen and each depends on 2 things happening concomitantly: photons could go directly $-\mathrm{P}(1$ to 3$) * \mathrm{P}(2$ to 4$)$ or could "cross over" - $\mathrm{P}(1$ to 4$) * \mathrm{P}(2$ to 3$)$. Resulting amplitudes for 2 possibilities are added, and is interference (as saw earlier), making final arrow vary in length, depending on relative location of points in space-time.

What if make 3 and 4 same point in space-time (Figure below)?


Space

Let's say both photons end up at point 3 , and see how this affects probability of event. Now have $\mathrm{P}(1$ to 3$) * \mathrm{P}(2$ to 3$)$ and $\mathrm{P}(2$ to 3$) * \mathrm{P}(1$ to 3$)$, which results in 2 identical arrows. When added, sum is twice length of either one, and produces final arrow whose square is 4 times square of either arrow alone. Because 2 arrows are identical, are always "lined up".

In other words, interference doesn't fluctuate according to relative separation between point 1 and 2 ; is always positive. If didn't think about always positive interference of 2 photons, should have thought that would get twice probability, on average. Instead, get 4 times probability all the time. When many photons are involved, this more-than-expected probability increases even further.

This results in number of practical effects. Can say that photons tend to get in same condition, or "state" (way amplitude to find one varies in space). Chance that atom emits photon is enhanced if some photons (in state that atom can emit into) already present. This phenomenon of "stimulated emission" discovered by Einstein when launched quantum theory proposing photon model of light. Lasers work on basis of this phenomenon.
If made same comparison with fake, spin-zero electrons, same thing would happen. But in real world, where electrons polarized, something very different happens: two arrows $\mathrm{E}(1$ to 3$) * \mathrm{E}(2$ to 4$)$ and $\mathrm{E}(1$ to 4$) * \mathrm{E}(2$ to 3$)$, are subtracted - one of them is turned $180^{\circ}$ before are added. When points 3 and 4 are same, two arrows have same length and direction and thus cancel out when are subtracted (Figure right).


That means electrons, unlike photons, do not like to go to same place; avoid each other like plague - no two electrons with same polarization can be at same point in space-time - called "exclusion principle".

Exclusion principle turns out to be origin of great variety of chemical properties of atoms. One proton exchanging photons with one electron dancing around called a hydrogen atom. Two protons in same nucleus exchanging photons with two electrons (polarized in opposite directions) called a helium atom. Chemists have complicated way of counting: instead of saying "one, two, three, four, five protons", they say, "hydrogen, helium, lithium, beryllium, boron".

Are only two states of polarization available to electrons, so in atom with three protons in nucleus exchanging photons with three electrons - condition called lithium atom - third electron is farther away from nucleus than other two (which have used up nearest available space), and exchanges fewer photons. Causes electron to easily break away from own nucleus under influence of photons from other atoms. Large number of such atoms close together easily lose third electrons to form sea of electrons swimming around from atom to atom. This sea of electrons reacts to any small electrical force (photons), generating current of electrons - am describing lithium metal conducting electricity. Hydrogen and helium atoms do not lose their electrons to other atoms. They are "insulators".

All atoms - more than one hundred different kinds - made up of certain number of protons exchanging photons with same number of electron. Patterns in which gather complicated and offer enormous variety of properties: some are metals, some are insulators, some are gases, others are crystals; there are soft things, hard things, colored things, and transparent things - terrific cornucopia of variety and excitement that comes from exclusion principle and repetition again and again and again of three very simple actions $P(A$ to $B), E(A$ to $B)$, and $j$. (If electrons in world were unpolarized, all atoms would have similar properties: electrons would all cluster together, close to nucleus of own atom, and would not be easily attracted to other atoms to make chemical reactions.

Might wonder how such simple actions could produce such complex world. Because phenomena see in world are result of enormous intertwining of tremendous numbers of photon exchanges and interferences. Knowing 3 fundamental actions is very small beginning toward analyzing any real situation, where is such a multitude of photon exchanges going on that is impossible to calculate experience has to be gained as to which possibilities are more important. Thus invent such ideas as "index of refraction" or "compressibility" or "valence" to help us calculate in approximate way when there's an enormous amount of detail going on underneath. Analogous to knowing rules of chess - which are fundamental and simple - compared to being able to play chess well, which involves understanding character of each position and nature of various situations - which is much more advanced and difficult.

Branches of physics that deal with questions such as why iron (with 26 protons) magnetic, while copper (with 29) not, or why one gas transparent and another one not, are called "solid-state physics", or "liquid-state physics", or "honest physics". Branch of physics that found 3 simple little actions (easiest part) called "fundamental physics" - chose name in order to make other physicists feel uncomfortable!
Most interesting problems - and certainly most practical problems - obviously in solid-state physics. But someone said there is nothing so practical as a good theory, and theory of quantum electrodynamics is definitely a good theory!
Finally, return to number 1.00115965221 , number from earlier that has been measured and calculated so carefully. Number represents response of electron to external magnetic field something called "magnetic moment". When Dirac first worked out rules to calculate number, used formula for E ( A to B ) and got very simple answer, which will consider in our units as 1 . Diagram for first approximation of magnetic moment of electron
 very simple - an electron goes from place to place in space-time and couples with photon from magnet (Figure right).

After some years was discovered that this value not exactly 1 , but slightly more - something like 1.00116 . This correction worked out for first time in 1948 by Schwinger as $\mathrm{j} * \mathrm{j}$ divided by $2 \pi$, and due to alternative way electron can go from place to place: instead of going directly from one point to another, electron goes along for while and suddenly emits photon; then (horrors) absorbs own photon (Figure right).


Perhaps something "immoral" about that, but electron does it! To calculate arrow for this alternative, have to make arrow for every place in space-time that photon can be emitted and every place can be absorbed -> will be two extra E(A to B)'s, a P(A to B), and two extra j's, all multiplied together. Students learn how to do this simple calculation in elementary quantum electrodynamics course, in second year of graduate school

But wait: experiments have measured behavior of an electron so accurately that have to consider still other possibilities in our calculations - all ways electron can go from place to place with four extra couplings (Figure below).


There are three ways electron can emit and absorb two photons. There's also new, interesting possibility (at right Figure to left): one photon emitted; makes positron-electron pair, and - again, if hold "moral" objections - electron and positron annihilate, creating new photon that is ultimately absorbed by electron. That possibility also has to be figured in!

Took two "independent groups of physicist two years to calculate this next term, and then another year to find out was a mistake - experimenters had measured value to be slightly different, and it looked for awhile that theory didn't agree with experiment for first time, but no: was mistake in arithmetic. How could two groups make same mistake"? Turns out that near end of calculation two groups compared notes and ironed out differences between their calculations, so were not really independent.

Term with six extra j's involves even more possible ways event could happen - draw few of them for you now (Figure below).


Space

Took twenty years to get extra accuracy figured into theoretical value of magnetic moment of an electron. Meanwhile experimenters made even more detailed experiments and added few more digits onto number - and theory still agreed with it.

So, to make our calculations, make these diagrams, write down what they correspond to mathematically, and add amplitudes - straightforward, "cook- book" process.

Therefore, can be done by machines. Now that have super-duper computers, have begun to compute term with eight extra j's. At present time theoretical number is 1.00115965246 ; experimentally, its
1.00115965221 , plus or minus 4 in last decimal place. Some of uncertainty in theoretical value (about 4 in last decimal place) is due to computer's rounding off numbers; most of it (about 20) is due to the fact that value of j not exactly known. Term for eight extra j's involves something like 900 diagrams, with hundred thousand terms each - fantastic calculation - and being done right now.

Sure that in few more years, theoretical and experimental numbers for magnetic moment of electron will be worked out to still more places. Of course, not sure whether two values will still agree. That, one can never tell until one makes calculation and does experiments.

Have come full circle to number chose to "intimidate" you with at beginning. Hope understand significance of number much better now: represents extraordinary degree to which been constantly checking that strange theory of quantum electrodynamics is indeed correct.
Throughout have delighted in showing that price of gaining such an accurate theory has been erosion of common sense. Must accept some very bizarre behavior: amplification and suppression of probabilities, light reflecting from all parts of a mirror, light travelling in paths other than a straight line, photons going faster or slower than conventional speed of light, electrons going backwards in time, photons suddenly disintegrating into positron-electron pair, and so on. That must do, in order to appreciate what Nature really doing underneath nearly all phenomena see in world.

With exception of technical details of polarization, have described framework by which understand all these phenomena. Draw amplitudes for every way an event can happen and add them when would have expected to add probabilities under ordinary circumstances; multiply amplitudes when would have expected to multiply probabilities. Thinking of everything in terms of amplitudes may cause difficulties at first because of their abstraction, but after while, one gets used to strange language. Underneath so many of phenomena see every day are only 3 basic actions: one is described by simple coupling number, j ; other two functions - $\mathrm{P}(\mathrm{A}$ to B$)$ and $\mathrm{E}(\mathrm{A}$ to B$)$ - both of which closely related. That's all there is to it, and from it all rest of laws of physics come.

However, before finish, make few additional remarks. Can understand spirit and character of quantum electrodynamics without including technical detail of polarization. But sure feel uncomfortable unless say something about what been leaving out. Photons, turns out, come in 4 different varieties, called polarizations, that are geometrically related to directions of space and time. Thus are photons polarized in $\mathrm{X}, \mathrm{Y}, \mathrm{Z}$, and T directions. (Perhaps heard somewhere that light comes in only two states of polarization - for example, photon going in Z direction can be polarized at right angles, either in X and Y direction.

Well, guessed it: in situations where photon goes a long distance and appears to go at speed of light, amplitudes for Z and T terms exactly cancel out. But for virtual photons going between proton and electron in atom, it is T component that is most important.

In similar manner, electron can be in one of 4 conditions that also related to geometry, but in somewhat more subtle manner. Call these conditions $1,2,3$, and 4 . Calculating amplitude for an electron going from point A to point B in space-time becomes somewhat more complicated, because can now ask questions such as, "What is amplitude that electron liberated in condition 2 at point A arrives in condition 3 at the point B?" The 16 possible combinations - coming from 4 different conditions an electron can start at A and 4 different conditions can end up in at B-are related in simple mathematical way to formula for that $\mathrm{E}(\mathrm{A}$ to B$)$ told you about.

For photon, no such modification necessary. Thus photon polarized in X direction at A will still be polarized in X direction at B , arriving with amplitude $\mathrm{P}(\mathrm{A}$ to B$)$.

Polarization produces large number of different possible couplings. Could ask, for example, "What is amplitude that an electron in condition 2 absorbs photon polarized in X direction and thereby turns into electron in condition 3?" All possible combinations of polarized electrons and photons do not couple, but those that do, do so with same amplitude $j$, but sometimes with an additional turn of arrow by some multiple of $90^{\circ}$.

These possibilities for different kinds of polarization and nature of couplings can all be deduced in very elegant and beautiful manner from principles of quantum electrodynamics and two further assumptions: 1) results of an experiment are not affected if apparatus with which are making experiments is turned in some other direction, and 2) also doesn't make any difference if apparatus in spaceship moving at some arbitrary speed. (-> principle of relativity.)

This elegant and general analysis shows that every particle must be in one or another class of possible polarizations, which call spin 0 , spin $1 / 2$, spin 1 , spin $3 / 2$, spin 2 and so on. Different classes behave in different ways. Spin 0 particle is simplest - has just one component - not effectively polarized at all. (fake electrons and photons that have been considering are spin 0 particles. So far, no fundamental spin 0 particles have been found.) Real electron is example of spin $1 / 2$ particle, and real photon is example of a spin 1 particle. Both spin $1 / 2$ and spin 1 particles have four components. Other types would have more components, such as spin 2 particles, with ten components.

Connection between relativity and polarization is simple and elegant, but can't explain simply and elegantly! (would take lot of time to do it.) Although details of polarization are not essential to understanding spirit and character of quantum electrodynamics, they are, of course, essential to correct calculation of any real process, and often have profound effects.

Have been concentrating on relatively simple interactions between electrons and photons at very small distances, in which only few particles are involved. Now make one or two remarks about how these interactions appear in larger world, where very, very large numbers of photons are being exchanged. On such large scale, calculation of arrows gets very complicated.
There are, however, some situations not so difficult to analyze. Are circumstances, for example, where amplitude to emit photon by source independent of whether another photon has been emitted. Can happen when source very heavy (nucleus of atom), or when very large number of electrons all moving same way, such as up and down in antenna of broadcasting station or going around in coils of an electromagnet. Under such circumstances large number of photons are emitted, all exactly same kind. Amplitude of an electron to absorb photon in such an environment independent of whether it or any other electron has absorbed other photons before. Therefore entire behavior can be given by just this amplitude for an electron to absorb a photon, which depends only on electron's position in space and time. Physicists use ordinary words to describe this circumstance. They say electron is moving in an external field.

Physicists use word "field" to describe quantity that depends on position in space and time. Temperatures in air provide good example: they vary according to where and when you make your measurements.
When take polarization into account, are more components to the field. (are 4 components corresponding to amplitude to absorb each of different kinds of polarization ( $\mathrm{X}, \mathrm{Y}, \mathrm{Z}, \mathrm{T}$ ) photon might be in - technically called vector and scalar electromagnetic potentials. From combinations of these, classical physics derives more convenient components called electric and magnetic fields.)

In situation where electric and magnetic fields varying slowly enough, amplitude for electron to travel over very long distance depends on path it takes. As saw earlier in case of light, most important paths are ones where angles of amplitudes from nearby paths are nearly same. Result is that particle doesn't necessarily go in straight line.

This brings us all the way back to classical physics, which supposes that there are fields and that electrons move through them in such a way as to make a certain quantity least. (Physicists call this quantity "action" and formulate this rule as "principle of least action".) One example of how rules of quantum electrodynamics produce phenomena on large scale. Just wanted to remind you that effects see on large scale and strange phenomena see on small scale are both produced by interaction of electrons and photons, and are all described, ultimately, by theory of quantum electrodynamics.

## Loose Ends

First, going to talk about problems associated with theory of quantum electrodynamics itself, supposing that all there is in world is electrons and photons. Then will talk about relation of quantum electrodynamics to rest of physics.

Most shocking characteristic of theory of quantum electrodynamics is crazy framework of amplitudes, which might think indicates problems of some sort! However, physicists have been fiddling around with amplitudes for more than fifty years now, and have gotten very used to it.

Furthermore, all new particles and new phenomena that are able to observe fit perfectly with everything that can be deduced from such a framework of amplitudes, in which probability of an event is square of final arrow whose length determined by combining arrows in funny ways (with interferences, and so on). So framework of amplitudes has no experimental doubt about it: can have all philosophical worries you want as to what amplitudes mean (if, indeed, mean anything at all), but because physics is experimental science and framework agrees with experiment, good enough for us so far.

There is set of problems associated with theory of quantum electrodynamics that has to do with improving method of calculating sum of all little arrows - various techniques that are available in different circumstances - that take graduate students three or four years to master. Since are technical problems, not going to discuss them here, just matter of continuously improving techniques for analyzing what theory really has to say in different circumstances.

But is one additional problem that is characteristic of theory of quantum electrodynamics itself, which took 20 years to overcome. Has to do with ideal electrons and photons and numbers $n$ and $j$.
If electrons ideal, and went from point to point in space-time only by direct path (left in Figure below), then would be no problem: n would simply be mass of electron (which can determine by observation), and j would simply be its "charge" (amplitude for electron to couple with photon). Can also be determined by experiment.


But no such ideal electrons exist. Mass observe in laboratory is that of real electron, which emits and absorbs own photons from time to time, and therefore depends on E (A to B), which


Experimentally measured amplitude for electron to couple with photon, mysterious number, e , is number determined by experiments that include all "corrections" for photon going from point to point in spacetime, of which two shown here. When calculating, need number, $j$, that does not include these corrections, but includes only photon going directly from point to point. Difficulty exists with computing this j that is similar to difficulty in computing value of n .

Since the mass and charge of an electron are affected by these and all other alternatives, experimentally measured mass, $m$, and experimentally measured charge $e$, of electron are different from numbers use in our calculations, $n$ and $j$
If were definite mathematical connection between $n$ and $j$ on one hand, and $m$ and $e$ on other, would still be no problem: would simply calculate what values of n and j need to start with in order to end up with observed values, $m$ and $e$. (if calculations didn't agree with $m$ and $e$, would jiggle original $n$ and $j$ around until they did.)

Let's see how actually calculate m . Write a series of terms that is something like series saw for magnetic moment of electron: first term has no couplings - just $\mathrm{E}(\mathrm{A}$ to B$)$ - and represents ideal electron going directly from point to point in space-times Second term has two couplings and represents photon being emitted and absorbed. Then come terms with four, six, and eight couplings, and so on (some of these "corrections" are shown earlier).

When calculating terms with couplings, must consider (as always) all possible points where couplings could occur, right down to cases where two coupling points are on top of each other - with zero distance between them. Problem is, when try to calculate all way down to zero distance, equation blows up in our face and gives meaningless answers - things like infinity. This caused lot of trouble when theory of quantum electrodynamics first came out. People getting infinity for every problem tried to calculate! (One should be able to go down to zero distance in order to be mathematically consistent, but that's where there is no $n$ or j that makes any sense; that's where trouble is.)

Instead of including all possible coupling points down to distance of zero, if one stops calculation when distance between coupling points very small - say, $10^{-30}$ centimeters, billions and billions of times smaller than anything observable in experiment (presently $10^{-16}$ centimeters) - then are definite values for n and j that can use so that calculated mass comes out to match m observed in experiments, and calculated charges matches observed charge, e. Now, here's catch: if somebody else comes along and stops their calculation at different distance - say, $10^{-40}$ centimeters - their value for $n$ and $j$ needed to get same $m$ and e come out different!

20 years later,(1949), Hans Bethe and Victor Weisskopf noticed something: if 2 people who stopped at different distances to determine n and j from same m and e then calculated answer to other problem each using appropriate but different values of $n$ and $j$ - when all the arrows from all terms were included, their answers to this other problem came out nearly the same! In fact, closer to zero distance that calculations for n and j were stopped, better final answers for other problem would agree! Schwinger, Tomonaga, and Feynman independently invented ways to make definite calculations to confirm that it is true (got prizes for that). People could finally calculate with theory of quantum electrodynamics!

So appears that only things that depend on small distances between coupling points are values for n and j $=$ theoretical numbers that are not directly observable anyway; everything else, which can be observed, seems not to be affected.

Shell game that play to find n and j is technically called "renormalization". But no matter how clever the word, is what would call dippy process! Having to resort to such hocus-pocus has prevented us from proving that theory of quantum electrodynamics is mathematically self-consistent. Surprising that theory still hasn't been proved self-consistent one way or other by now; suspect renormalization not mathematically legitimate. What is certain is that do not have good mathematical way to describe theory of quantum electrodynamics: such a bunch of words to describe the connection between $n$ and $j$ and $m$ and $e$ is not good mathematics.

Another interesting way of describing this difficulty is to say that perhaps idea that two points can be infinitely close together wrong - assumption that can use geometry down to last notch false. If make minimum possible distance between two points as small as $10^{-100}$ centimeters (smallest distance involved in any experiment today around $10^{-16}$ centimeters), infinities disappear, all right - but other inconsistencies arise, such as total probability of an event adds up to slightly more or less than $100 \%$, or get negative energies in infinitesimal amounts. Been suggested that these inconsistencies arise because haven't taken into account effects of gravity - which are normally very, very weak, but become important at distances of $10^{-33} \mathrm{~cm}$.

## Will fix everything later when do Standard Model!

Most profound and beautiful question associated with observed coupling constant, e - amplitude for real electron to emit or absorb a real photon. Is simple number that has been experimentally determined to be close to - 0.08542455 . (physicist friends won't recognize number, because like to remember it as inverse of its square: about 137.03597 with uncertainty of about 2 in last decimal place. Has been mystery ever since was discovered more than 50 years ago, and all good theoretical physicists put this number up on their walls and worry about it.)

Immediately would like to know where number for coupling comes from: is it related to $\pi$, or perhaps to base of natural logarithms? Nobody knows. It's one of greatest damn mysteries of physics: magic number that comes to us with no understanding by man. Might say "hand of God" wrote number , and " we don't know how He pushed His pencil". Know what kind of a dance to do experimentally to measure number very accurately, but don't know what kind of dance to do on computer to make this number come out - without putting it in secretly!

Good theory would say e is square root of 3 over $2 \pi$ squared, or something. Have been, from time to time, suggestions what e is, but none of them useful.

First, Arthur Eddington proved by pure logic that number physicists like had to be exactly 136, experimental number at that time. Then, as more accurate experiments showed number closer to 137, Eddington discovered slight error in earlier argument, and showed by pure logic again that number had to be integer 137! Every once in a while, someone notices that certain combination of pi's and e's (base of natural logarithms), and 2's and 5's produces mysterious coupling constant, but it is fact not fully appreciated by people who play with arithmetic that would be surprised how many numbers can make out of pi's and e's and so on. Therefore, throughout history of modern physics, has been paper after paper by people who have produced an e to several decimal places, only to have next round of improved experiments disagree with it.

Even though have to resort to dippy process to calculate j today, possible that someday legitimate mathematical connection between j and e will be found. Would mean that j is mysterious number, and from it comes e. In such case would doubtless be another batch of papers that tell us how to calculate $j$ "with our bare hands", so to speak, proposing that j is 1 divided by $4 \pi$, or something.

That exposes all problems associated with quantum electrodynamics.

## Let us now look at particle physics as Feynman knew it in the 1980s.

First, must immediately say that rest of physics has not been checked anywhere nearly as well as electrodynamics: some of things going to tell you are good guesses, some are partly worked-out theories, and others are pure speculation. Therefore presentation going to look like relative mess, compared to earlier; will be incomplete and lacking in many details. Nevertheless, turns out that structure of theory of QED serves as excellent basis for describing other phenomena in rest of physics.

Begin by talking about protons and neutrons, which make up nuclei of atoms.

When protons and neutrons first discovered was thought were simple particles, but very soon became clear were not simple - simple in sense that amplitude to go from one point to another could be explained by formula E (A to B), but with different number n stuck in. For example, proton has magnetic moment that, if calculated in same way as for electron, should be close to 1 . But in fact, experimentally comes out completely crazy - 2.79 ! Therefore was soon realized that something's going on inside proton that is not accounted for in equations of quantum electrodynamics. And neutron, which should have no magnetic interaction at all if really neutral, has magnetic moment of about 11.93! So was known for long time that something fishy is going on inside neutron as well.

Was also problem of what holds neutrons and protons together inside nucleus. Was realized right away that could not be exchange of photons, because force holding nucleus is much greater than that required to knock an electron away from an atom in same proportion that atomic bomb more destructive than dynamite: exploding dynamite is rearrangement of electron patterns, while exploding atomic bomb is rearrangement of proton-neutron patterns.

To find out more about what holds nuclei together, many experiments made in which protons with higher and higher energies smashed into nuclei. Was expected that only protons and neutrons would come out. But when energies became sufficiently large, new particles came out. 1st were pions, then lambdas, and sigmas, and rhos, and ran out of alphabet. Then came particles with numbers (masses), sigma 1190 and sigma 1386. Soon became clear that number of particles in world was open-ended, and depended on amount of energy used to break apart nucleus. Are over 400 such particles at present. Can't accept 400 particles; that's too complicated!

Great inventors like Murray Gell-Mann nearly went crazy trying to figure out rules by which all these particles behave, and in early 1970s came up with quantum theory of strong interactions (or "quantum chromodynamics"), whose main actors are particles called "quarks".

All of particles made of quarks come in 2 classes: some, like proton and neutron, made of 3 quarks ("baryons"); others, pions, made of quark and anti-quark ("mesons").

Make table of fundamental particles as appear today (Figure right). Begin with particles that go from point to point according to formula $\mathrm{E}(\mathrm{A}$ to B ) - modified by same kind of polarization rules as electron called "spin $1 / 2$ " particles. 1st of these particles is electron, and mass number is 0.511 in units use all the time, called MeV . MeV very small - appropriate to such particles - about $1.78 \times 10^{-27}$ grams

Under electron leave space (occupied later), and under that list two types of quarks - d and u. Mass of quarks not exactly known; good guess is around 10 MeV for each. (Neutron is slightly heavier than proton, which seems to imply - as will see in moment - that d quark somewhat heavier than u quark.)

Next to each particle list charge, or coupling constant, in terms of -j , number for couplings with photons with sign reversed. Makes charge for electron -1 , consistent with convention started by Benjamin Franklin
 that been stuck with ever since. For d quark amplitude to couple with photon is $-1 / 3$, and for $u$ quark is $+2 / 3$. (Had Benjamin Franklin known about quarks, might have at least made charge of electron -1 !)

Now, charge of proton is +1 , and neutron's charge is zero. With some fiddling about with numbers, can see that proton - made of 3 quarks must be two u's and a d, while neutron - also made of three quarks must be two d's and a u (Figure right).

What holds quarks together? Is it photons going back and forth? (Because d quark has charge of $-1 / 3$ and $u$ quark has charge of $+2 / 3$, quarks, as well as electrons, emit and absorb photons.) No, electrical forces far too weak to do that. Something else has been invented to go back and forth and hold quarks together! something called "gluons", 25 Gluons are an example of another type of particle called "spin 1" (as photons); they go from point to point with amplitude determined by exactly same formula as for photons, $\mathrm{P}(\mathrm{A}$ to B$)$. Amplitude for gluons to be emitted or absorbed by quarks is mysterious number, g , much larger than j (Figure right).


Notice names: "photon" comes from Greek word for light; "electron" comes from Greek word for amber - beginning of electricity. But as modern physics progressed, names of particles have shown deteriorating interest in classical Greek until make up such words as "gluons". Can you guess why called "gluons"? In fact, $d$ and $u$ stand for words, but I don't want to confuse you - a d quark is no more "down" than a u quarks is "up". Incidentally, the d-ness or u-ness of a quark is called its "flavor".

Diagrams make of quarks exchanging gluons are very similar to pictures draw for electrons exchanging photons (Figure right).

So similar, in fact, might say physicists have no imagination - just copied theory of quantum electrodynamics for strong interactions! And you're right: that's what we did, but with little twist.


Quarks have an additional type of polarization not related to geometry. Idiot physicists, unable to come up with any wonderful Greek words anymore, call this type of polarization by unfortunate name of "color", which has nothing to do with color in normal sense.

At particular time, quark can be in one of 3 conditions, or "colors" - R, G, or B (can you guess what they stand for?). Quark's "color" can be changed when quark emits or absorbs gluon. Gluons come in 8 different types, according to "colors" can couple with. For example, if red quark changes to green, emits red-antigreen gluon - gluon that takes red from quark and gives it green ("antigreen" means gluon carrying green in opposite direction). This gluon could be absorbed by green quark, which changes to red (Figure right).


Are 8 different possible gluons, such as red-antired, red-antiblue, redantigreen, and so on (you'd think there'd be 9, but for technical reasons, one is missing). Theory not very complicated. Complete rule of gluons is: gluons couple with things having "color" - just requires little bookkeeping to keep track of where "colors" go.
Interesting possibility created by rule: gluons can couple with other gluons (Figure right). For instance, green-antiblue gluon meeting red-
 antigreen gluon results in red-antiblue gluon. Gluon theory very simple just make diagram and follow "colors". Strengths of couplings in all diagrams determined from coupling constant for gluons, $g$.

Gluon theory really not great deal different in form from quantum electrodynamics. How, then, does it compare with experiment? For example, how does observed magnetic moment of proton compare with value calculated from theory?

Experiments very accurate - show magnetic moment to be 2.79275 . At very best, theory can only come up with $2.7 \pm 0.3$ - if sufficiently optimistic about accuracy of analysis - error of $10 \%$ which is 10,000 time less accurate than experiment!

Have simple, definite theory that is supposed to explain all properties of protons and neutrons, yet can't calculate anything with it, because mathematics too hard for us. Reason can't calculate to any great accuracy because coupling constant for gluons, $g$ so much larger than for electrons. Terms with two, four, and even six couplings not just minor corrections to main amplitude; represent considerable contributions that can't be ignored. Thus are arrows from so many different possibilities that haven't been able to organize them in reasonable way to find out what final arrow is.

In books says that science is simple: make up theory and compare to experiment; if theory doesn't work, throw away and make new theory. Here have definite theory and hundreds of experiments, but can't compare them! Situation that never before existed in history of physics. Boxed in, temporarily, unable to come up with method of calculation. Snowed under by all the little arrows.

Despite difficulties in calculating with theory, do understand some things qualitatively about quantum chromodynamics (strong interactions of quarks and gluons). Objects made of quarks that see are "colored" neutral: groups of three quarks contain one quark of each "color", and quark-antiquark pairs have equal amplitude to be red-antired, green-antigreen, or blue-antiblue. Also understand why quarks can never be produced as individual particles - no matter how much energy is used to hit a nucleus against a proton, instead of seeing individual quarks come out, see jets of mesons and baryons (quarkantiquark pairs and groups of three quarks).

Quantum chromodynamics and quantum electrodynamics aren't all there is to physics. According to them, quark cannot change its "flavor": once u quark, always u quark; once d quarks, always d quark. But Nature behaves differently sometimes. There is form of radioactivity that happens slowly - kind that people worry about leaking out of nuclear reactors - called beta decay, which involves neutron changing into proton. Since neutron consists of two d's and a u-type quark while proton is made of two u's and a d, what really happens is that one of the neutron's d-type quarks changes into a u-type quark (Figure below).


Here's how it happens: d quark emits new thing like photon called W, which has coupling with electron and another new particle called an anti-neutrino, neutrino going backwards in time. Neutrino is another spin $1 / 2$ particle (like electron and quarks), but has no mass and no charge (does not interact with photons). Also does not interact with gluons; only couples with W (Figure below).

W is spin 1 type particle (like photon and gluon), that changes "flavor" of quark and takes away charge - $d$, charged $-1 / 3$, changes into $u$, charged $+2 / 3$, difference of -1 . (doesn't change quark's "color".) Because $\mathrm{W}^{-}$takes away charge of -1 (and antiparticles, $\mathrm{W}^{+}$, takes away charge of +1 ), can also couple with photon. Beta decay takes much longer than interactions of photons and electrons, so is thought that W must have very high mass (about $80,000 \mathrm{MeV}$ ), unlike photon and gluon. Have not been able to see W by itself because of very high energy
 required to knock loose particle with such very high mass.

After Feynman finished, high enough energies were achieved to produce W by itself, and mass was measured to be very close to value predicted by theory.

There is another particle, which could think of as neutral $W$, called $Z^{0}$. The $Z^{0}$ does not change charge of quark, but does couple with d quark, u quark, and electron, or neutrino (Figure below)


Interaction has misleading name of "neutral currents', and caused lot of excitement when was discovered few years ago. Theory of W's nice and neat if allow for 3-way coupling between 3 types of W's (Figure right).


Observed coupling constant for W 's same as for photon - in neighborhood of j . Therefore possibility exists that 3 W's and photon are all different aspects of same thing. Stephen Weinberg and Abdus Salam tried to combine quantum electrodynamics with what's called "weak interactions" (interactions with W's) into one quantum theory, and did it.
But if you just look at results they get can see glue, so to speak. Very clear that photon and 3 W 's are interconnected somehow, but at present level of understanding, connection difficult to see clearly - can still see "seams' in theories; have not yet been smoothed out so that connection becomes more beautiful and therefore, probably more correct.

So there you are: quantum theory has 3 main types of interaction - the "strong interactions" of quarks and gluons, the "weak interactions" of the W's, and the "electrical interactions" of photons. Only particles in world (according to this picture) are quarks (in "flavors" u and d with three "colors" each), gluons (eight combinations of R, G, and B), W's (charged $\pm 1,0$ ), neutrinos, electrons, and photons about twenty different particles of six different types (plus their anti-particles). That's not bad - about twenty different particles - except that's not all.
As nuclei were hit with protons of higher and higher energies, new particles kept coming out. One such particle was muon, which is in every way exactly same as electron, except that its mass much higher 105.8 MeV , compared to 0.511 for electron, or about 206 times heavier. Just as if God wanted to try out different number for mass! All of properties of muon are completely describable by theory of electrodynamics - coupling constant $j$ is same and $E(A$ to $B)$ is same; just put in different value of $n$.

Magnetic moment of muon been measured very accurately - has been found to be 1.001165924 (with uncertainty of 9 in last digit), while value for electron is 1.00115965221 (with uncertainty of 3 in last digit). Might be curious as to why magnetic moment of muon slightly higher than that of electron. One of diagrams drew had electron emitting photon that disintegrates into positron-electron pair (Figure right). There is also small amplitude that emitted photon could make a muon-antimuon pair, which is heavier than original electron. This is unsymmetrical, because when muon emits photon, if that photon makes positron-electron pair, pair is
 lighter than original muon. Theory of quantum electrodynamics accurately describes every electrical property of muon as well as electron.

Because muon has mass about 200 times higher than electron, "stopwatch hand" for muon turns 200 times more rapidly than that of electron. Has enabled us to test whether electrodynamics still behaves according to theory at distances 200 times smaller than been able to test before - although these distances are still more than 80 decimal places larger than distances at which theory alone might run into trouble with infinities.

Learned that electron can couple with W. When d-quark changes into u-quark, emitting W, can W couple with muon instead of an electron? Yes (Figure right).

What about anti-neutrino? In case of W coupling with muon, particle called mu-neutrino takes place of ordinary neutrino (call an electron-neutrino). So table of particles has 2 additional particles next to electron and neutrino - muon and muon-neutrino.


What about quarks? Very early on, particles were known that had to be made of heavier quarks than $u$ or $d$. Thus third quark, called s (for "strange") was included in list of fundamental particles. s quark has mass of about 200 MeV , compared to about 10 MeV for u and d quarks.

For many years thought that there were just 3 "flavors" of quarks $\mathrm{u}, \mathrm{d}$, and s - but in 1974 new particle called psi-meson was discovered that could not be made of three quarks. Was also very good theoretical argument that there had to be a fourth quark, coupled to s quark by W in same way that u and d quarks are coupled (Figure below).

"Flavor" of this quark called c, and c stands for "charm". Names are getting worse and worse!
Repetition of particles with same properties but heavier masses is complete mystery. What is this strange duplication of pattern? As Professor I. I. Rabi said of the muon when was discovered, "Who ordered that?"

Recently another repetition of list has begun. As go to higher and higher energies, Nature seems to keep piling on these particles as if to drug us. Have to tell you about them because I want you to see how apparently complicated world really looks. Would be very misleading if were to give you impression that since solved $99 \%$ of phenomena in world with electrons and photons, that other $1 \%$ of phenomena will take only $1 \%$ as many additional particles! Turns out that to explain that last $1 \%$, need 10 or 20 times as many additional particles.
So here we go again: with even higher energies used in experiments, even heavier electron, called "tau", found; has mass of about $1,800 \mathrm{MeV}$, heavy as two protons! tau-neutrino has been inferred. An now funny particle found implying new "flavor" of quark - this time it's b, for "beauty", and has charge of $-1 / 3$ (Figure below).


Now, want you to become high-class, fundamental theoretical physicists for moment, and predict something: new flavor of quark will be found, called t for "truth", with charge of $+2 / 3$, a mass of 40,000 MeV - and certainly true that it's there - evidence found for existence of $t$ quark with very high mass around $40,000 \mathrm{MeV}$.

Meanwhile experiments being done to see if cycle repeats yet again. At present time machines being built to look for even heavier electron than tau. If mass of supposed particle is $100,000 \mathrm{MeV}$, won't be able to produce it. If around $40,000 \mathrm{MeV}$, might make it.
Mysteries like these repeating cycles make very interesting to be theoretical physicist: Nature gives us such wonderful puzzles! Why does She repeat electron at 206 times and 3,640 times its mass?

One last remark to make things absolutely complete about particles. When d quark coupling to W changes into $u$ quark, also has small amplitude to change into c instead, When u quark goes to d quark, also has small amplitude to change into s quark, and
 even smaller amplitude to change into b quark (Figure right).

Thus W "screws things up" little bit and allows quarks to change from one column of table to another. Why quarks have these relative proportions for their amplitude to change to another type of quark utterly unknown.

So that's everything about rest of quantum physics. Terrible mix-up, and might say hopeless mess physics has got itself worked into. But has always looked like this. Nature has always looked like horrible mess, but as go along see patterns and put theories together; certain clarity comes and things get simpler. Mess just showed is much smaller than mess would have had to make 10 years ago, telling you about the more than four hundred particles. And think about mess at beginning of 20th century, when there was heat, magnetism, electricity, light, X-rays, ultraviolet rays, indices of refraction, coefficients of reflection and other properties of various substances, all of which have since put together into one theory, quantum electrodynamics.

Emphasize something. Theories about rest of physics are very similar to theory of quantum electrodynamics: all involve interaction of spin $1 / 2$ objects (electrons and quarks) with spin 1 objects (photons, gluons, or W's) within framework of amplitudes by which probability of an event is square of length of an arrow. Why are all these theories of physics so similar in their structure?

Number of possibilities. 1st is limited imagination of physicists: when see new phenomenon try to fit it into framework already have - until have made enough experiments, don't know that doesn't work. So when some fool physicist gives lecture at UCLA in 1983 and says, "This is the way it works, and look how wonderfully similar the theories are", not because Nature is really similar; because physicists have only been able to think of same damn thing, over and over again.

Another possibility is that it is same damn thing over an over again - that Nature has only one way of doing things, and She repeats her story from time to time.

3rd possibility is that things look similar because they are aspects of same thing - some larger picture underneath, from which things can be broken into parts that look different, like fingers on same hand. Many physicists working very hard trying to put together grand picture that unifies everything into one super-duper model. Delightful game, but at present time none of speculators agree with any of other speculators as to what grand picture is.

Exaggerating only slightly when say that most of these speculative theories have no more deep sense to them than your guess about possibility of $t$ quark, and guarantee that they are no better at guessing mass of $t$ quark than you are!

For example, appears that electron, neutrino, d quark, and u quark all go together - indeed, first two couple with W, as do last two. At present thought that quark can only change "colors" or "flavors". But perhaps quark could disintegrate into neutrino by coupling with undiscovered particle. Nice idea. What would happen? That would mean protons are unstable.

Somebody makes up theory: Proton is unstable. Make calculation and find that there would be no protons in universe anymore! So fiddle around with numbers, putting higher mass into new particle, and after much effort predict that proton will decay at rate slightly less than last measured rate proton has been shown not to decay at.

When new experiment comes along and measures proton more carefully, theories adjust themselves to squeeze out from pressure. Most recent experiment showed that proton doesn't decay at rate that is 5 times slower than what was predicted in last stand of theories. What do you think happened? Phoenix just rose again with new modification of theory that requires even more accurate experiments to check it. Whether proton decays or not is not known. To prove that it does not decay is very difficult.

Did not discuss gravitation. Reason is, gravitational influence between objects extremely small: force that is weaker by 1 followed by 40 zeros than electrical force between two electrons (perhaps 41 zeros). In matter, nearly all of electrical forces are spent holding electrons close to nucleus of atom, creating finely balanced mixture of pluses and minuses that cancel out. But with gravitation, only force is attraction, and keeps adding and adding as there are more and more atoms until at last, when get to these ponderously large masses that we are, can begin to measure effects of gravity - on planets, on ourselves, and so on.

Because gravitational force so much weaker than any of other interactions, impossible at present time to make any experiment sufficiently delicate to measure any effect that requires precision of quantum theory of gravitation to explain it. Even though there no way to test them, there are, nevertheless, quantum theories of gravity that involve "gravitons" (which would appear under new category of polarizations, called "spin 2"), and other fundamental particles (some with spin 3/2). Best of these theories not able to include particles that do find, and invents lot of particles that don't find. Quantum theories of gravity also have infinities in terms with couplings, but "dippy process" that is successful in getting rid of infinities in quantum electrodynamics doesn't get rid of them in gravitation. So not only have no experiments with which to check quantum theory of gravitation, also have no reasonable theory. Throughout this entire story remains one especially unsatisfactory feature: observed masses of particles, m . There is no theory that adequately explains these numbers. Use numbers in all our theories, but don't understand them - what they are, or where they come from. Believe that from fundamental point of view, this is very interesting and serious problem.

Lots of speculation about new particles is confusing, but complete discussion of rest of physics to show how character of those laws - framework of amplitudes, diagrams that represent interactions to be calculated, and so on - appears to be same as for theory of quantum electrodynamics, our best example of good theory.

