CHAPTER 1

Which Way? Both Ways: Particle-Wave Duality

We're out for a walk, when the dog spots a squirrel up ahead and takes off in pursuit. The squirrel flees into a yard and dodges around a small ornamental maple. Emmy doesn't alter her course in the slightest, and just before she slams into the tree, I pull her up short.

"What'd you do that for?" she asks, indignantly.

"What do you mean? You were about to run into a tree, and I stopped you."

"No I wasn't." She looks off after the squirrel, now safely up a bigger tree on the other side of the yard. "Because of quantum."

We start walking again. "Okay, you're going to have to explain that," I say.

"Well, I have this plan," she says. "You know how when I chase the bunnies in the backyard, when I run to the right of the pond, they go left, and get away?"

"Yes."

"And when I run to the left of the pond, they go right, and get away?"

"Yes."

"Well, I've thought of a new way to run, so they can't escape."

"What, through the middle of the pond?" It's only about eight inches deep and a couple of feet across.

"No, silly. I'm going to go both ways. I'll trap the bunnies between me."

"Uh-huh. That's an . . . interesting theory."

"It's not a theory, it's quantum physics. Material particles have wave nature and can diffract around objects. If you send a beam of electrons at a barrier, they'll go around it to the left and to the right, at the same time." She's really getting into this, and she doesn't even notice the cat sunning itself in the yard across the street. "So, I'll just make use of my wave nature, and go around both sides of the pond."

"And where does running headfirst into a tree come in?"

"Oh, well." She looks a little sheepish. "I thought I would try it out on something smaller first. I got a good running start, and I was just about to go around when you stopped me."

"Ah. Like I said, an interesting theory. It won't work, you know."

"You're not going to try to claim I don't have wave nature, are you? Because I do. It's in your physics books."

"No, no, you've got wave nature, all right. You've also got Buddha nature—"

"I'm an enlightened dog!"

"—which will do you about as much good. You see, a tree is big, and your wavelength is small. At walking speed, a twenty-kilogram dog like you has a wavelength of about 10^{-35} meters. You need your wavelength to be comparable to the size of the tree—maybe ten centimeters—in order to diffract around it, and you're thirty-four orders of magnitude off."

"I'll just change my wavelength by changing my momentum. I can run very fast."

"Nice try, but the wavelength gets *shorter* as you go faster. To get your wavelength up to the millimeter or so you'd need to diffract around a tree, you'd have to be moving at 10^{-30} meters per second, and that's impossibly slow. It would take a billion years to cross the nucleus of an atom at that speed, which is way too slow to catch a bunny."

"So, you're saying I need a new plan?"

"You need a new plan."

Her tail droops, and we walk in silence for a few seconds. "Hey," she says, "can you help me with my new plan?"

"I can try."

"How do I use my Buddha nature to go around both sides of the pond at the same time?"

I really can't think of anything to say to that, but a flash of gray fur saves me. "Look! A squirrel!" I say.

"Oooooh!" And we're off in pursuit.

Quantum physics has many strange and fascinating aspects, but the discovery that launched the theory was **particle-wave duality**, or the fact that both light and matter have particle-like and wavelike properties at the same time. A beam of light, which is generally thought of as a wave, turns out to behave like a stream of particles in some experiments. At the same time, a beam of electrons, which is generally thought of as a stream of particles, turns out to behave like a wave in some experiments. Particle and wave properties seem to be contradictory, and yet everything in the universe somehow manages to be both a particle and a wave.

The discovery in the early 1900s that light behaves like a particle is the launching point for all of quantum mechanics. In this chapter, we'll describe the history of how physicists discovered this strange duality. In order to appreciate just what a strange development this is, though, we need to talk about the particles and waves that we see in everyday life.

PARTICLES AND WAVES AROUND YOU: CLASSICAL PHYSICS

Everybody is familiar with the behavior of material particles. Pretty much all the objects you see around you—bones, balls, squeaky toys—behave like particles in the classical sense, with their motion determined by classical physics. They have different shapes, but you can predict their essential motion by imagining each as a small, featureless ball with some mass—a particle—and applying Newton's laws of motion.* A tennis ball and a long bone tumbling end over end look very different in flight, but if they're thrown in the same direction with the same speed, they'll land in the same place, and you can predict that place using classical physics.

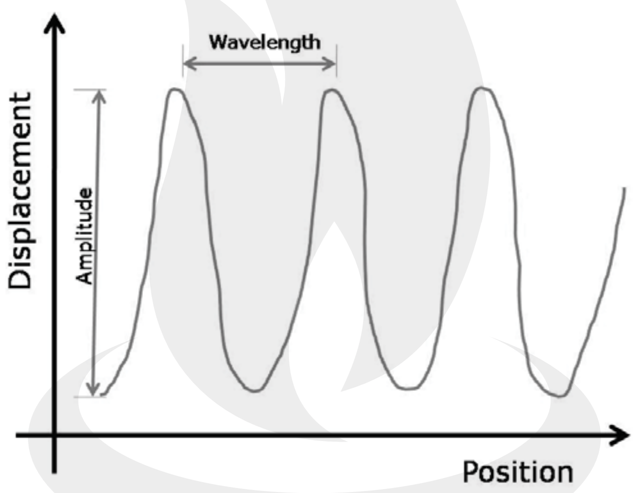
A particle-like object has a definite position (you know right where it is), a definite velocity (you know how fast it's moving, and in what direction), and a definite mass (you know how big it is). You can multiply the mass and velocity together, to find the **momentum**. A great big Labrador retriever has more momentum than a little French poodle when they're both moving at the same speed, and a fast-moving border collie has more momentum than a waddling basset hound of the same mass. Momentum determines what will happen when two particles collide. When a moving object hits a stationary one, the moving object will slow down, losing momentum, while the stationary object will speed up, gaining momentum.

The other notable feature of particles is something that seems almost too obvious to mention: particles can be counted. When you have some collection of objects, you can look at them and determine exactly how many of them you have—one bone, two squeaky toys, three squirrels under a tree in the backyard.

*Sir Isaac Newton, of the falling apple story, set forth three laws of motion that govern the behavior of moving objects. The first law is the principle of inertia, that objects at rest tend to remain at rest, and objects in motion tend to remain in motion unless acted on by an external force. The second law quantifies the first, and is usually written as the equation $F = ma$, force equals mass times acceleration. The third law says that for every action there is an equal and opposite reaction—a force of equal strength in the opposite direction. These three laws describe the motion of macroscopic objects at everyday speeds, and form the core of classical physics.

Waves, on the other hand, are slipperier. A wave is a moving disturbance in something, like the patterns of crests and troughs formed by water splashing in a backyard pond. Waves are spread out over some region of space by their nature, forming a pattern that changes and moves over time. No physical objects move anywhere—the water stays in the pond—but the pattern of the disturbance changes, and we see that as the motion of a wave.

If you want to understand a wave, there are two ways of looking at it that provide useful information. One is to imagine taking a snapshot of the whole wave, and looking at the pattern of the disturbance in space. For a single simple wave, you see a pattern of regular peaks and valleys, like this:



As you move along the pattern, you see the medium moving up and down by an amount called the "amplitude" of the wave. If you measure the distance between two neighboring crests of the wave (or two troughs), you've measured the "wavelength," which is one of the numbers used to describe a wave.

The other thing you can do is to look at one little piece of the wave pattern, and watch it for a long time—imagine watching a duck bobbing up and down on a lake, say. If you watch carefully, you'll see that the disturbance gets bigger and smaller in a very regular way—sometimes the duck is higher up, sometimes lower down—and makes a pattern in time very much like the pattern in space. You can measure how often the wave repeats itself in a given amount of time—how many times the duck reaches its maximum height in a minute, say—and that gives you the "frequency" of the wave, which is another critical number used to describe the wave. Wavelength and frequency are related to each other—longer wavelengths mean lower frequency, and vice versa.

You can already see how waves are different from particles: they don't have a position. The wavelength and the frequency describe the pattern as a whole, but there's no single place you can point to and identify as *the* position of the wave. The wave itself is a disturbance spread over space, and not a physical thing with a definite position and velocity. You can assign a velocity to the wave pattern, by looking at how long it takes one crest of the wave to move from one position to another, but again, this is a property of the pattern as a whole.

You also can't count waves the way you can count particles—you can say how many crests and troughs there are in one particular area, but those are all part of a single wave pattern. Waves are continuous where particles are discrete—you can say that you have one, two, or three particles, but you either have waves, or you don't. Individual waves may have larger or smaller amplitudes, but they don't come in chunks like particles do. Waves don't even add together in the same way that particles do—sometimes, when you put two waves together, you end up with a bigger wave, and sometimes you end up with no wave at all.

Imagine that you have two different sources of waves in the same area—two rocks thrown into still water at the same time, for example. What you get when you add the two waves together depends on how they line up. If you add the two waves together such that the crests of one wave fall on top of the crests of the other, and the troughs of one wave fall in the troughs of the other (such waves are called "in phase"), you'll get a larger wave than either of the two you started with. On the other hand, if you add two waves together such that the crests of one wave fall in the troughs of the other and vice versa ("out of phase"), the two will cancel out, and you'll end up with no wave at all.

This phenomenon is called *interference,* and it's perhaps the most dramatic difference between waves and particles.

"I don't know . . . that's pretty weird. Do you have any other examples of interference? Something more . . . doggy?"

"No, I really don't. That's the point—waves are dramatically different than particles. Nothing that dogs deal with on a regular basis is all that wavelike."

"How about, 'Interference is like when you put a squirrel in the backyard, and then you put a dog in the backyard, and a minute later, there's no more squirrel in the backyard.' "

"That's not interference, that's prey pursuit. Interference is more like putting a squirrel in the backyard, then putting a second squirrel in the backyard one second later, and finding that you have no squirrels at all. But if you wait *two* seconds before putting in the second squirrel, you find four squirrels."

"Okay, that's just weird."

"That's my point."

"Oh. Well, good job, then. Anyway, why are we talking about this?"

"Well, you need to know a few things about waves in order to understand quantum physics."

"Yeah, but this just sounds like math. I don't like math. When are we going to talk about physics?"

"We are talking about physics. The whole point of physics is to use math to describe the universe."

"I don't want to describe the universe, I want to catch squirrels."

"Well, if you know how to describe the universe with math, that can help you catch squirrels. If you have a mathematical model of where the squirrels are now, and you know the rules governing squirrel behavior, you can use your model to predict where they'll be later. And if you can predict where they'll be later . . ."

"I can catch squirrels!"

"Exactly."

"All right, math is okay. I still don't see what this wave stuff is for, though."

"We need it to explain the properties of light and sound waves, which is the next bit."

WAVES IN EVERYDAY LIFE: LIGHT AND SOUND

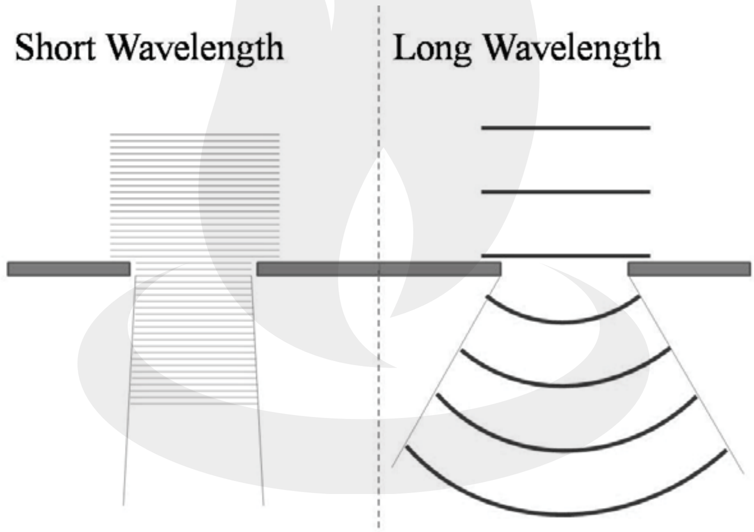
We deal with two kinds of waves in everyday life: light and sound. Though these are both examples of wave phenomena, they appear to behave very differently. The reasons for those differences will help shed some light (pardon the pun) on why it is that we don't see dogs passing around both sides of a tree at the same time.

Sound waves are pressure waves in the air. When a dog barks, she forces air out through her mouth and sets up a vibration that travels through the air in all directions. When it reaches another dog, that sound wave causes vibrations in the second dog's eardrums, which are turned into signals in the brain that are processed as sound, causing the second dog to bark, producing more waves, until nearby humans get annoyed.

Light is a different kind of wave, an oscillating electric and magnetic field that travels through space—even the emptiness of outer space, which is why we can see distant stars and galaxies. When light waves strike the back of your eye, they get turned into signals in the brain that are processed to form an image of the world around you.

The most striking difference between light and sound in everyday life has to do with what happens when they encounter an obstacle. Light waves travel only in straight lines, while sound waves seem to bend around obstacles. This is why a dog in the dining room can hear a potato chip hitting the kitchen floor, even though she can't see it.

The apparent bending of sound waves around corners is an example of **diffraction**, which is a characteristic behavior of waves encountering an obstacle. When a wave reaches a barrier with an opening in it, like the wall containing an open door from the kitchen into the dining room, the waves passing through the opening don't just keep going straight, but fan out over a range of different directions. How quickly they spread depends on the wavelength of the wave and the size of the opening through



On the left, a wave with a short wavelength encounters an opening much larger than the wavelength, and the waves continue more or less straight through. On the right, a wave with a long wavelength encounters an opening comparable to the wavelength, and the waves diffract through a large range of directions.

which they travel. If the opening is much larger than the wavelength, there will be very little bending, but if the opening is comparable to the wavelength, the waves will fan out over the full available range.

Similarly, if sound waves encounter an obstacle like a chair or a tree, they will diffract around it, provided the object is not too much larger than the wavelength. This is why it takes a large wall to muffle the sound of a barking dog—sound waves bend around smaller obstacles, and reach people or dogs behind them.

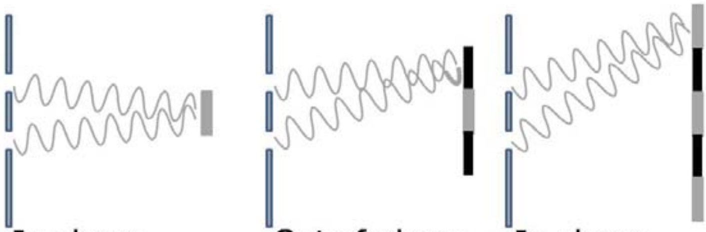
Sound waves in air have a wavelength of a meter or so, close to the size of typical obstacles—doors, windows, pieces of furniture. As a result, the waves diffract by a large amount, which is why we can hear sounds even around tight corners.

Light waves, on the other hand, have a very short wavelength—less than a thousandth of a millimeter. A hundred wavelengths of visible light will fit in the thickness of a hair. When light waves encounter everyday obstacles, they hardly bend at all, so solid objects cast dark shadows. A tiny bit of diffraction occurs right at the edge of the object, which is why the edges of shadows are always fuzzy, but for the most part, light travels in a straight line, with no visible diffraction.

If we don't readily see light diffracting like a wave, how do we know it's a wave? We don't see diffraction around everyday objects because they're too large compared to the wavelength of light. If we look at a small enough obstacle, though, we can see unmistakable evidence of wave behavior.

In 1799 an English physicist named Thomas Young did the definitive experiment to demonstrate the wave nature of light. Young took a beam of light and inserted a card with two very narrow slits cut in it. When he looked at the light on the far side of the card, he didn't just see an image of the two slits, but rather a large pattern of alternating bright and dark spots.

Young's double-slit experiment is a clear demonstration of the diffraction and interference of light waves. The light pass-



An illustration of double-slit diffraction. On the left, the waves from two different slits travel exactly the same distance, and arrive in phase to form a bright spot. In the center, the wave from the lower slit travels an extra half-wavelength (darker line), and arrives out of phase with the wave from the upper slit. The two cancel out, forming a dark spot in the pattern. On the right, the wave from the lower slit travels a full extra wavelength, and again adds to the wave from the upper slit to form a bright spot.

ing through each of the slits diffracts out into a range of different directions, and the waves from the two slits overlap. At any given point, the waves from the two slits have traveled different distances, and have gone through different numbers of oscillations. At the bright spots, the two waves are in phase, and add together to give light that is brighter than light from either slit by itself. At the dark spots, the waves are out of phase, and cancel each other out.

Prior to Young's experiment, there had been a lively debate about the nature of light, with some physicists claiming that light was a wave, and others (including Newton) arguing that light was a stream of tiny particles. Interference and diffraction are phenomena that only happen with waves, though, so after Young's experiment (and subsequent experiments by the French physicist Augustin Fresnel), everybody was convinced that light was a wave. Things stayed that way for about a hundred years.

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"How does this relate to going around both sides of a tree? I'm not interested in going through slits, I want to catch bunnies."

"The same basic process happens when you put small solid obstacles into the path of a light beam. You can think of the light that goes around to the left and the light that goes around to the right of the obstacle as being like the waves from two different slits. They take different paths to their destination, and thus can be either in phase or out of phase when they arrive. You get a pattern of bright and dark spots, just like when you use slits."

"Oh. I guess that makes sense. So, I just need to get the bunnies to stand at the spots where I'm in phase with me?"

"No, because of the wavelength thing. We'll get to that in a minute. I need to talk about particles, first."

"Okay. I can be patient. As long as it doesn't take too long."

THE BIRTH OF THE QUANTUM: LIGHT AS A PARTICLE

The first hint of a problem with the wave model of light came from a German physicist named Max Planck in 1900. Planck was studying the **thermal radiation** emitted by all objects. The emission of light by hot objects is a very common phenomenon (the best-known example is the red glow of a hot piece of metal), and something so common seems like it ought to be easy to explain. By 1900, though, the problem of explaining how much light of different colors was emitted (the "spectrum" of the light) had thus far defeated the best physicists of the nineteenth century.

Planck knew that the spectrum had a very particular shape, with lots of light emitted at low frequencies and very little at high frequencies, and that the peak of the spectrum—the frequency at which the light emitted is brightest—depends only on the object's temperature. He had even discovered a formula to describe the characteristic shape of the spectrum, but was stymied when he tried to find a theoretical justification for the formula. Every method he tried predicted much more light at high frequencies than was observed. In desperation, he resorted to a mathematical trick to get the right answer.

Planck's trick was to imagine that all objects contained fictitious "oscillators" that emit light only at certain frequencies. Then he said that the amount of energy (E) associated with each oscillator was related to the frequency of the oscillation (f) by a simple formula:

$$E = hf$$

where h is a constant. When he first made this odd assumption, Planck thought he would use it just to set up the problem, and then use a common mathematical technique to get rid of the imaginary oscillators and this extra constant h. Much to his surprise, though, he found that his results made sense only if he kept the oscillators around—if h had a very small but nonzero value.

Today, h is known as **Planck's constant** in his honor, and has the value 6.626×10^{-34} kg m^2/s (that's 0.000000000000000 000000000000000000006626 kg m^2/s). It's a very small number indeed, but definitely not zero.

Planck's trick amounts to treating light, which physicists thought of as a continuous wave, as coming in discrete chunks, like particles. Planck's "oscillators" could only emit light in discrete units of brightness. This is a little like imagining a pond where waves can only be one, two, or three centimeters high, never one and a half or two and a quarter. Everyday waves don't work that way, but that's what Planck's mathematical model requires.

These "oscillators" are also what puts the "quantum" in "quantum physics." Planck referred to the specific levels of energy in his oscillators as "quanta" (the plural of "quantum," from the

Latin word for "how much"), so an oscillator at a given frequency might contain one quantum (one unit of energy, *hf*), two quanta, three quanta, and so on, but never one and a half or two and a quarter. The name for the steps stuck, and came to be applied to the entire theory that grew out of Planck's desperate trick.

Though he's often given credit for inventing the idea of light quanta, Planck never really believed that light came in discrete quanta, and he always hoped that somebody would find a clever way to derive his formula without resorting to trickery.

The first person to talk seriously about light as a quantum particle was Albert Einstein in 1905, who used it to explain the **photoelectric effect**. The photoelectric effect is another physical effect that seems like it ought to be simple to describe: when you shine light on a piece of metal, electrons come out. This forms the basis for simple light sensors and motion detectors: light falling on a sensor knocks electrons out of the metal, which then flow through a circuit. When the amount of light hitting the sensor changes, the circuit performs some action, such as turning lights on when it gets dark, or opening doors when a dog passes in front of the sensor.

The photoelectric effect ought to be readily explained by thinking of light as a wave that shakes atoms back and forth until electrons come out, like a dog shaking a bag of treats until they fly all over the kitchen. Unfortunately, the wave model comes out all wrong: it predicts that the energy of the electrons leaving the atoms should depend on the intensity of the light—the brighter the light, the harder the shaking, and the faster the bits flying away should move. In experiments, though, the energy of the electrons doesn't depend on the intensity at all. Instead, the energy depends on the frequency, which the wave model says shouldn't matter. At low frequencies, you never get any electrons no matter how hard you shake, while at high frequency, even gentle shaking produces electrons with a good deal of energy.

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"Physicists are silly."

"I beg your pardon?"

"Well, any dog knows *that*. When you get a bag with treats in it, you always shake it as fast as you can, as hard as you can. That's how you get the treats out."

"Yes, well, what can I say? Dogs have an excellent intuitive grasp of quantum theory."

"Thank you. We're cute, too."

"Of course, the point of physics is to understand *why* the treats come out when they do."

"Maybe for you. For dogs, the point is to get the treats."

Einstein explained the photoelectric effect by applying Planck's formula to light itself. Einstein described a beam of light as a stream of little particles, each with an energy equal to Planck's constant multiplied by the frequency of the light wave (the same rule used for Planck's "oscillators"). Each **photon** (the name now given to these particles of light) has a fixed amount of energy it can provide, depending on the frequency; and some minimum amount of energy is required to knock an electron loose. If the energy of a single photon is more than the minimum needed, the electron will be knocked loose, and carry the rest of the photon's energy with it. The higher the frequency, the higher the single photon energy and the more energy the electrons have when they leave, exactly as the experiments show. If the energy of a single photon is lower than the minimum energy for knocking an electron out, nothing happens, explaining the lack of electrons at low frequencies.*

Describing light as a particle was a hugely controversial idea in 1905, as it overturned a hundred years' worth of physics and

*You might wonder why you can't put together two low-energy photons to provide enough energy to free an electron. This would require two photons to hit the same electron at the same instant, and that almost never happens.

requires a very different view of light. Rather than a continuous wave, like water poured into a dog's bowl, light has to be thought of as a stream of discrete particles, like a scoop of kibble poured into a bowl. And yet each of those particles still has a frequency associated with it, and somehow they add up to give an interference pattern, just like a wave.

Other physicists in 1905 found this deeply troubling, and Einstein's model took a while to gain acceptance. The American physicist Robert Millikan hated Einstein's idea, and performed a series of extremely precise photoelectric effect experiments in 1916 hoping to prove Einstein wrong.* In fact, his results confirmed Einstein's predictions, but even that wasn't enough to get the photon idea accepted. Wide acceptance of the photon picture didn't come until 1923, when Arthur Holly Compton did a famous series of experiments with X-rays that demonstrated unmistakably particle-like behavior from light: he showed that photons carry momentum, and this momentum is transferred to other particles in collisions.

If you take the Planck formula for the energy of a single photon, and combine it with equations from Einstein's special relativity, you find that a single photon of light ought to carry a small amount of momentum, given by the formula:

$$p = h/\lambda$$

where p is the symbol for momentum and λ is the wavelength of the light.

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*Millikan thought the Einstein model lacked "any sort of satisfactory theoretical foundation," and described its success as "purely empirical," which is pretty nasty by physics standards. Ironically, those quotes are from the first paragraph of the paper in which he conclusively confirms the predictions of the theory.

"I thought you said there wasn't any relativity in this book?"

"I said the book isn't *about* relativity. That's not the same thing. Some ideas from relativity are important to quantum physics, as well."

"What's relativity got to do with this, though?"

"Well, what relativity says is that because a photon has some energy, it must have some momentum, even though it doesn't have any mass."

"So . . . it's an $E = mc^2$ thing?"

"Not exactly, but it's similar. Photons have momentum because of their energy in the same way that objects have energy because of their mass. And nice job dropping an equation in there."

"Please. Even inferior dogs know $E = mc^2$. And I am an *exceptional* dog."

A photon with a small wavelength has a lot of momentum, while a photon with a large wavelength has very little. That means that the interaction between a photon of light and a stationary object ought to look just like a collision between two particles: the stationary object gains some energy and momentum, and the moving photon loses some energy and momentum. We don't notice this because the momentum involved is tiny—Planck's constant is a very small number—but if we look at an object with a very small mass, like an electron, and photons with a very short wavelength (and thus a relatively high momentum), we can detect the change in momentum.

In 1923, Compton bounced X-rays with an initial wavelength of 0.0709 nanometers* off a solid target (X-rays are just light with an exceptionally short wavelength, compared to about 500 nm for visible light). When he looked at the X-rays that scattered off the target, he found that they had longer wavelengths, indicating that they had lost momentum (X-rays bouncing off

*A nanometer is 10^{-9} m, or one billionth of a meter (0.000000001 m).

at 90 degrees from their original direction had a wavelength of 0.0733 nm, for example). This loss of momentum is exactly what should happen if light is a particle: when an X-ray photon comes in and hits a more or less stationary electron in a target, it gives up some of its momentum to the electron, which starts moving. After the collision, the photon has less momentum, and thus a longer wavelength, exactly as Compton observed.

The amount of momentum lost also depends on the angle at which the photon bounces off—a photon that glances off an electron doesn't lose very much momentum, while one that bounces almost straight back loses a lot. Compton measured the wavelength at many different angles, and his results exactly fit the theoretical prediction, confirming that the shift was from collisions with electrons, and not some other effect.

Einstein, Millikan, and Compton all won Nobel prizes for demonstrating the particle nature of light. Taken together, Millikan's photoelectric effect experiments and Compton's scattering experiments were enough to get most physicists to accept the idea of light as being made up of a stream of particles.*

As strange as the idea of light as a particle was, though, what came next was even stranger.

*A few die-hard theorists still resisted the idea of photons, because even the Compton effect can be explained without photons, though it's very complicated. The last resistance collapsed in 1977, when incontrovertible proof of the existence of photons was provided in an experiment by Kimble, Dagenais, and Mandel that looked at the light emitted by single atoms. The seventy-two-year gap between Einstein's proposal and its final acceptance tells you something about the stubbornness of physicists confronted with a new idea. It can be as difficult to separate a physicist from a cherished model as it is to drag a dog away from a well-chewed bone.

INTERFERING ELECTRONS: PARTICLES AS WAVES

Also in 1923, a French Ph.D. student named Louis Victor Pierre Raymond de Broglie* made a radical suggestion: he argued that there ought to be symmetry between light and matter, and so a material particle such as an electron ought to have a wavelength. After all, if light waves behave like particles, shouldn't particles behave like waves?

De Broglie suggested that just as a photon has a momentum determined by its wavelength, a material object like an electron should have a wavelength determined by its momentum:

$$\lambda = h/p$$

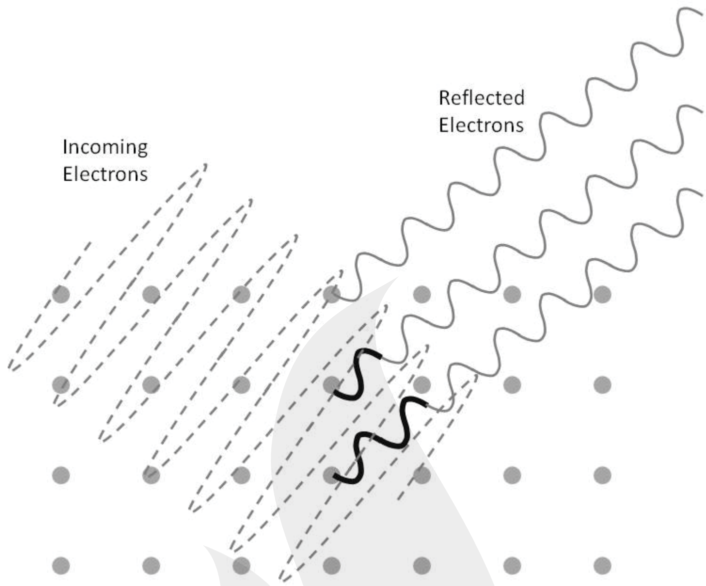
which is just the formula for the momentum of a photon (page 24) turned around to give the wavelength. The idea has a certain mathematical elegance, which was appealing to theoretical physicists even in 1923, but it also seems like patent nonsense—solid objects show no sign of behaving like waves. When de Broglie presented his idea as part of his Ph.D. thesis defense, nobody knew what to make of it. His professors weren't even sure whether to give him the degree or not, and resorted to showing his thesis to Einstein. Einstein proclaimed it brilliant, and de Broglie got his degree, but his idea of electrons as waves had little support until two experiments in the late 1920s showed incontrovertible proof that electrons behaved like waves.

*The proper pronunciation of Louis de Broglie's surname (his collection of names reflects his aristocratic background—he was the 7th Duc de Broglie) is the source of much confusion among American physicists. I've heard "de-BRO-lee," "de-BRO-glee," and "de-BROY-lee," among others. The correct French pronunciation is apparently something close to "de-BROY," only with a gargly sort of sound to the vowel that you need to be French to make.

In 1927, two American physicists, Clinton Davisson and Lester Germer, were bouncing electrons off a surface of nickel, and recording how many bounced off at different angles. They were surprised when their detector picked up a very large number of electrons bouncing off at one particular angle. This mysterious result was eventually explained as the wavelike diffraction of the electrons bouncing off different rows of atoms in their nickel target. The beam of electrons penetrated some distance into the nickel, and part of the beam bounced off the first row of atoms in the nickel crystal,* while other parts bounced off the second, and the third, and so on. Electrons reflecting from all these different rows of atoms behaved like waves. The waves that bounced off atoms deeper in the crystal traveled farther on the way out than the ones that bounced off atoms closer to the surface. These waves interfered with one another, like light waves passing through the different slits in Young's experiment (though with many slits, not just two). Most of the time, the reflected waves were out of phase and canceled one another out. For certain angles, though, the extra distance traveled was exactly right for the waves to add in phase and produce a bright spot, which Davisson and Germer detected as a large increase in the number of electrons reflected at that angle. The de Broglie formula for assigning a wavelength to the electron predicts the Davisson and Germer result perfectly.†

*"Crystal," to a physicist, refers to any solid with a regular and orderly arrangement of atoms in it. This includes the clear and sparkly things that we normally associate with the word, but also a lot of metals and other substances.

†Ironically, Davisson and Germer succeeded only because they broke a piece of their apparatus. They didn't see any diffraction in the first experiments they did, because their nickel target was made up of many small crystals, each producing a different interference pattern, and the bright spots from the different patterns ran together. Then they accidentally let air into their vacuum system. In the process of repairing the damage, they melted the target, which recrystallized into a single large crystal, producing a single, clear



Diffraction of electrons off a crystal of nickel. An incoming electron beam (dashed line) passes into a regular crystal of atoms, and bits of the wave (individual electrons) reflect off different atoms in the crystal. Electrons reflected from deeper in the crystal travel a longer distance on the way out (darker line), but for certain angles, that distance is a multiple of a full wavelength, and the waves leaving the crystal add in phase to give the bright spot seen by Davisson and Germer.

• • •

"Wait, how does that work? If there are lots of slits, shouldn't there be lots of spots?"

"Not really. When you add the waves together, you still get a pattern of bright and dark spots, but as you use more slits, the bright spots get brighter and narrower, and the dark spots get darker and wider."

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diffraction pattern. Sometimes, the luckiest thing a physicist can do is to break something important.

"So, if I run through the picket fence to the neighbors' yard, I'll get brighter and narrower on the other side?"

"You'd be narrower, all right, but it wouldn't be a bright idea. The point here is that the 'slits' that Davisson and Germer were using were so close together that they could only see one bright spot in the region where they could put their detector. With a different crystal, or faster-moving electrons, they would've seen more spots."

At around the same time, George Paget Thomson at the University of Aberdeen carried out a series of experiments in which he shot beams of electrons at thin films of metal, and observed diffraction patterns in the transmitted electrons (such patterns are produced in essentially the same way as the pattern in the Davisson-Germer experiment). Diffraction patterns like those seen by Davisson and Germer and Thomson are an unmistakable signature of wave behavior, as Thomas Young showed in 1799, so their experiments provided proof that de Broglie was right, and electrons have wave nature. De Broglie won the Nobel Prize in Physics in 1929 for his prediction, and Davisson and Thomson shared a Nobel Prize in 1937 for demonstrating the wave nature of the electron.*

Following the experiments of Davisson and Germer and Thomson, scientists showed that all subatomic particles behave like waves: beams of protons and neutrons will diffract off samples of atoms in exactly the same way that electrons do. In fact, neutron diffraction is now a standard tool for determining the structure of materials at the atomic level: scientists can deduce how atoms are arranged by looking at the interference patterns

*In one of the great bits of Nobel trivia, Thomson's father, J. J. Thomson of Cambridge, won the 1906 Nobel Prize in Physics for demonstrating the particle nature of the electron. This presumably led to some interesting dinner-table conversation in the Thomson household.

that result when a beam of neutrons bounces off their sample. Knowing the structure of materials at the atomic level allows materials scientists to design stronger and lighter materials for use in cars, planes, and space probes. Neutron diffraction can also be used to determine the structure of biological materials like proteins and enzymes, providing critical information for scientists searching for new drugs and medical treatments.

EVERYTHING IS MADE OF WAVES: INTERFERENCE OF MOLECULES

So, if all material objects are made up of particles with wave properties, why don't we see dogs diffracting around trees? If a beam of electrons can diffract off two rows of atoms, why can't a dog run around both sides of a tree to trap a bunny on the far side? The answer is the wavelength: as with the sound and light waves discussed earlier, the dramatically different behavior of dogs and electrons encountering obstacles is explained by the difference in their wavelengths. The wavelength is determined by the momentum, and a dog has a lot more momentum than an electron.

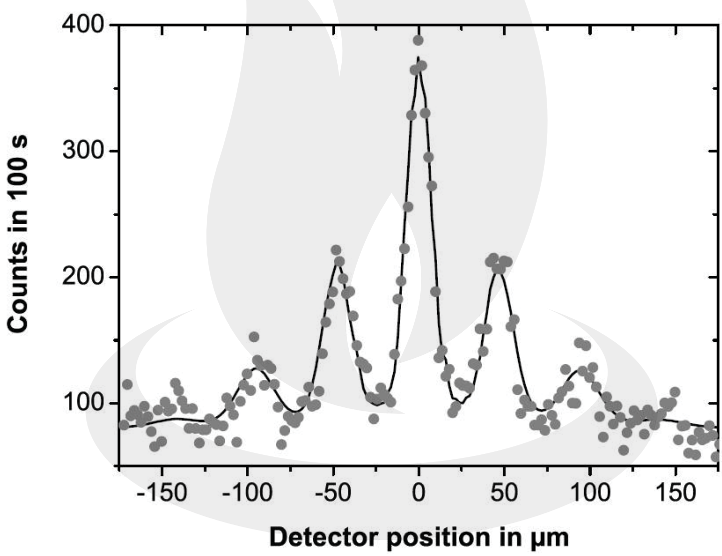
The wavelength of a material object is given by Planck's constant divided by the momentum, which is mass multiplied by velocity. Planck's constant is a tiny number, but so is the mass of an electron—about 10^{-30} kilograms, or 0.0000000000000000 00000000000001 kg. Davisson and Germer's electrons, moving at the brisk speed of six million meters per second, had a wavelength of about a tenth of a nanometer (0.0000000001 m). That's extremely small, but it's about half the distance between two nickel atoms, just right for seeing diffraction (just like sound waves with half-meter wavelengths will readily diffract through one-meter-wide doors).

The wavelength of a 50-pound (about 20 kg) dog out for a stroll, on the other hand, is about 10^{-35} meters (0.00000000000

0000000000000000000000001 m), or a millionth of a billionth of a billionth of the wavelength of Davisson and Germer's electrons. How does that compare to the size of a tree? Well, a dog's wavelength compared to the distance between two atoms is like the distance between two atoms compared to the diameter of the solar system. There's no chance of seeing the wave associated with a dog diffract off a crystal of nickel, let alone pass around both sides of a tree at the same time.

There's a lot of room between a beam of electrons and a dog, though, so what is the biggest material object that has been shown to have observable wave nature?

In 1999, a research group at the University of Vienna headed



The interference pattern produced by a beam of molecules passing through an array of narrow slits. The extra lumps to either side of the central peak are the result of diffraction and interference of the molecules passing through the slits. (Reprinted with permission from O. Nairz, M. Arndt, and A. Zeilinger, Am. J. Phys. *71, 319 [2003]. Copyright 2003, American Association of Physics Teachers.)*

by Dr. Anton Zeilinger observed diffraction and interference with molecules consisting of 60 carbon atoms bound together into a shape like a tiny soccer ball, each with a mass about a million times that of an electron. They shot these soccer-ball-shaped molecules toward a detector, and when they looked at the distribution of molecules downstream, they saw a single narrow beam. Then they sent the beam through a silicon wafer with a collection of very small slits cut into it, and looked at the distribution of molecules on the far side of the slits. With the slits in place, the initial narrow peak grew broader, with distinct "lumps" to either side. Those lumps, like the bright and dark spots seen by Thomas Young shining light through a double slit, or the electron diffraction peaks seen by Davisson and Germer, are an unmistakable signature of wave behavior. Molecules passing through the slits spread out and interfere with one another, just like light waves.

In subsequent experiments, the Zeilinger group demonstrated the diffraction of even larger molecules, adding 48 fluorine atoms to each of their original 60-carbon-atom molecules. These molecules have a mass about three million times the mass of one electron, and stand as the current record for the most massive object whose wave nature has been observed directly.

As the mass of a particle increases, its wavelength gets shorter and shorter, and it gets harder and harder to see wave effects directly. This is why nobody has ever seen a dog diffract around a tree; nor are we likely to see it any time soon. In terms of physics, though, a dog is nothing but a collection of biological molecules, which the Zeilinger group has shown have wave properties. So, we can say with confidence that a dog has wave nature, just the same as everything else.

"So, which are they *really*?"

"What do you mean?"

"Well, are electrons really particles acting like waves, or are photons waves acting like particles?"

"You're asking the wrong questions. Or, rather, you're giving the wrong answers. The real answer is 'Door Number Three.' Electrons and photons are both examples of a third sort of object, which is neither just a wave nor just a particle, but has some wave properties and some particle properties at the same time."

"So, it's like a squirunny?"

"A what?"

"A critter that's something like a squirrel, and something like a bunny. A squirunny."

"I prefer 'quantum particle,' but I guess that's the basic idea. Everything in the universe is built of these quantum particles."

"That's pretty weird."

"Oh, that's just the beginning of the weird stuff . . ."