Chapter 17

Wave-Particle Duality, and Quantum Mechanics

The purpose of this chapter is to help you become comfortable with the radical ideas of quantum mechanics, to help you combine creativity and critical thinking so you can be freely imaginative without getting silly and illogical.

Sections 17.1 and 17.2 explain wave-particle duality, and try to convince you that "yes, things really are strange". Section 17.3 describes what quantum mechanics is and isn't, and "why things are stable and dependable". Then Section 17.4 discusses quantum uncertainty, and shows that "no, things are not as strange as some people say they are".

These sections should be read in order, either all at once, or one at a time as your class studies each successive topic. However you do it, I suggest that you read this chapter more than once — it will help you understand and digest the ideas in this fascinating area of science that is the foundation of "modern physics".

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OPTIONAL: **Section 17.95 discusses nuclear force, the $e = mc^2$ conservation of mass-energy, and using logarithms to solve "half life" nuclear decay problems.**

17.1 Wave-Particle Duality: Photons

A bullet is an example of a *particle*. It has mass and velocity, participates in collisions, follows a definite trajectory that can be analyzed using Newton's Laws, is count-able (you can say "there are 4 bullets on the table"), has definite boundaries and volume (two bullets cannot both occupy the same volume at the same time).

The properties of waves aren't as obvious. It is easy to observe some things that two common waves (sound and light) do, but these waves are invisible so it isn't easy to observe what they are. Section 9.1 uses easy-to-visualize water waves to describe characteristics that all waves have: velocity, frequency, wavelength and amplitude. Unlike particles, two or more waves can simultaneously occupy the same volume; the *interference* this produces is discussed in Sections 9.2 and 15.1-15.3.

Before 1905 the scientific model of light was simple, logical, easy to understand, and wrong. A long-running argument about whether light is a wave or a particle was apparently settled in 1801 when the double-slit experiments of Young, described in Section 15.1, provided convincing evidence for the *wave* nature of light. In 1864 Maxwell showed that light is an *electromagnetic wave*. But our knowledge of light was not yet complete*, as shown by the Michelson-Morley experiment (in 1887) and the photoelectric effect.

***And we don't know it all now, either!**

In 1905 Einstein published papers explaining the Michelson-Morley experiment (with the *special theory of relativity* that is described in Section 16.1-16.6) and the photoelectric effect (by answering "Is light a wave or a particle?" with "yes, yes").

The Photoelectric Effect

In the late 1800's, experimenters discovered that when light shines on metals, electrons are ejected from atoms at the surface of the metal. For example, when blue light (with a frequency of 6.2×10^{14} cycles/s) shines on sodium metal, electrons begin to leave the surface immediately even if the light is dim. The rate of electron ejection is proportional to brightness; if light intensity is increased by a factor of 10, electrons leave the surface 10 times as often. But red light (frequency = 4.3×10^{14} cycles/s) does not eject electrons from the sodium atoms, even if the light is bright and shines on the surface for a long time.

These results cannot be explained satisfactorily using the pre-1905 model of light, which predicts that 1) the ability to eject electrons should depend on the intensity of light but not on its color, and 2) with extremely weak light there should be a delay between the start of illumination and the start of electron ejection. { If a block of ice is illuminated by sunlight for 30 minutes more energy is absorbed, and more ice melts, than if the block is in the sun for only 1 minute. Similarly, the classical pre-1905 model predicts that when metal is illuminated with bright red light for a long time, the metal's electrons will absorb a lot of energy, enough to let them escape from the metal surface. With dim blue light for a short time, it predicts very little energy absorption, not enough to eject electrons.} The observed results are just the opposite of these classical-theory predictions. Why? ==[is this OK? are there better ways to show classical theory's inability to explain photoelectric results?]

To answer this question, Einstein proposed that light is emitted, transmitted and absorbed as particles he called *photons,* with each photon having an energy of

$$E_{photon} = h\ f$$

where **h** is *Planck's constant* (with an SI value of 6.63×10^{-34} J·s), and **f** is the frequency of the electromagnetic light wave. By substituting "$f = c/\lambda$" from Section 9.1, this equation is transformed into: $E_{photon} = hc/\lambda$.

A red-light photon has $E_{photon} = hf = (6.63 \times 10^{-34})(4.3 \times 10^{14}) = 2.9 \times 10^{-19}$ Joules, and a blue-light photon has $E_{photon} = (6.63 \times 10^{-34})(6.2 \times 10^{14}) = 4.1 \times 10^{-19}$ Joules.

If the intensity of blue light increases by a factor of 10, there are 10 times as many photons, but each photon still carries the same amount of energy: 4.1×10^{-19} J.

When blue light shines on sodium metal, a blue photon can give one electron the "extra energy" it needs to escape from the surface. But a red photon doesn't have enough energy to eject an electron. Turning up the brightness of red light doesn't help, because this just produces more low-energy photons that can't get the job done. { Usually, the energy contributed by one red photon is not stored to make it easier for an electron to be ejected by the next red photon that is absorbed. During the normal process that leads to ejection of an electron there is no "teamwork"; <u>only one photon interacts with one electron</u> and either the photon, acting by itself, can provide enough energy to eject the photon, or it can't.}

Energy Accountability

To eject an electron from sodium metal, a photon must have an energy of at least 3.8×10^{-19} Joules; this is called the *work function,* W_o. If a blue photon has 4.1×10^{-19} J of energy, 3.8×10^{-19} J can be used to eject an electron that has $.3 \times 10^{-19}$ J of kinetic energy. Do you see that energy is conserved?

photon energy	=	energy needed to remove electron	+	leftover energy
$h\,f$	=	W_o	+	KE_{max}
4.1×10^{-19} J	=	3.8×10^{-19} J	+	$.3 \times 10^{-19}$ J

The maximum kinetic energy an electron can escape with is KE_{max}. {If a photon penetrates into the metal and ejects an electron from an atom that is beneath the surface, the electron loses energy by collisions within the metal. If it is able to reach the surface and escape, this electron will have less than $.3 \times 10^{-19}$ J of KE.}

In "$E_{photon} = h\,f$", the particle-like and wave-like properties of light both appear in the same equation! The energy of a single photon (a light particle) depends on its frequency (a characteristic of light waves).

As discussed in Problem 17-#, it took many years and some deep thinking (plus careful experiments like the *Compton effect* in 1922) for the theory of photon wave-particle duality to develop the widespread acceptance it enjoys today.

17.2 Wave-Particle Duality: Electrons

In 1923 Louis DeBroglie reasoned that if something we had previously considered to be a **wave** (light) has **particle-like properties**, maybe things we usually think of as **particles** (like electrons, protons, bullets,...) have **wave-like properties**.

He introduced the concept of *matter waves,* and proposed that the relationship between their momentum and wavelength is the same as it is for a photon: $h/p = \lambda$, where **h** is Planck's constant, **p** (which is mv) is the particle's momentum, and λ is the *deBroglie wavelength* of the particle. { I remember this equation by thinking help: for "$h = \lambda\, p$", h equals lambda (the name for the Greek λ) p.}

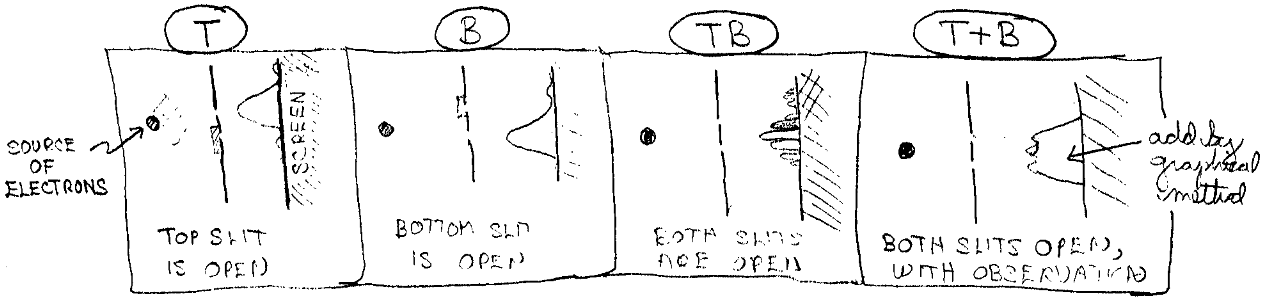
In 1927 experiments where a beam of electrons interacted with a "multiple-slit grating" produced wave interference effects similar to those described for a light beam in Section 15.1. Later experiments confirmed the wave-like properties of protons, neutrons and other particles.

==cut? Double-slit experiments have never been done with electrons. But when electrons interact with a "multiple-slit grating" that is, as explained in Section 15.1, very similar to double slits, electrons have the same kind of wave-particle behavior as photons. Because a double-slit screen is easier to analyze than a grating, and scientists are confident that the behavior of electrons is that is described below (for electrons) is valid. .} ==[what a mess. how to describe this quickly, clearly, honestly, without distracting students from main issues??] just cut this?

{ Double-slit experiments have not been done with electrons. But electrons and photons exhibit the same kind of wave-particle behavior when they interact with multiple-slit gratings, and scientists are confident that the double-slit behavior that is described below (for electrons) is valid.} ==cut?

When a beam of light photons passes through the double slit apparatus described in Section 15.1, *diffraction* and *interference* occur because of the wave-like property of photons. If a similar experiment was done with electrons, we would see the same kind of diffraction and interference, due to the wave-like property of electrons.

The diagrams below shows what would happen if electrons T) only go through the Top slit, B) only go through the Bottom slit, TB) can go through either of the slits. Diagram T+B is discussed later. {As in Chapter 15, the curved line represents intensity; the peak of a curve is the place where electrons are most likely to hit the screen. If a piece of "electron-sensitive photographic film" is attached to the screen, an intensity peak will be a bright spot on the film.}



In T and B we see a *single-slit diffraction pattern,* as described in Section 15.2. In TB the electrons diffract as they pass through each slit; then waves from the slits *superimpose* to produce a *double-slit interference pattern,* just as in Section 15.1.

What happens if we do a double-slit experiment (like TB) with the intensity of the electron beam turned down very low, so low that only one electron at a time passes through the slits? Electrons pass through the slits and hit the screen one at a time. If we make a "time lapse photograph" over an extremely long period of time to get a cumulative record of where electrons have hit the screen, we find that electron intensity forms the same double-slit interference pattern as in TB above.

This pattern can only be formed if there are two waves — passing through the two slits — that interfere with each other. But how can there be two waves if intensity is so low that only one electron interacts with the slits at any given time? A double slit pattern shows that each electron behaves as if part of its wave-nature goes through the top slit and part of it goes through the bottom slit. This is strange, but true; <u>the wave-like nature of a single electron can interfere with itself</u>!

But we find that whenever an electron interacts with the screen, it does so as a "whole electron particle". We never see part of an electron arrive at one place on the screen and the rest of it at another place. And when an electron travels between the slits and screen there is no electrical repulsion between different parts of the electron wave — the electron does not behave as if it is "spread out". The electron has self-interference but not self-repulsion. Very strange.

It is reasonable to assume that if an electron only interacts with the screen as a whole-electron particle, then it will pass through the slits in a similar way — either the whole electron-particle goes through the top slit, or it goes through the bottom slit. This seems logical, but is it correct?

There is a way to test this assumption. If we shine light on the electrons as they go through the slits (like taking a photograph while using a flashbulb) in a way that tells us whether an electron has gone through the top slit, the bottom slit, or "both slits at the same time", the electrons that hit the screen will form pattern T+B. Why do I call this pattern T+B? If we keep separate records of the three categories, we find that electrons going through the top slit form a T pattern, electrons going through the bottom slit form a B pattern, and we don't find any electrons that "go through both slits at the same time". If we add the two single-slit patterns (T pattern + B pattern) they form the T+B pattern. {If our method of detection isn't totally efficient, some electrons may be able to sneak through without being observed. When these electrons hit the wall they collectively form a TB double-slit interference pattern.}

With both slits open the electrons form pattern TB, but with both slits open <u>and</u> observation (to see which slit they go through) they form T+B. When electrons are observed their behavior changes! It seems that **interaction with photons during observation** makes the electron-wave change from "part of the wave going through each slit" to "all of the wave being in one place, with none going through the other slit", and this eliminates the double-slit interference.

Sometimes Analogy is Inadequate

An electron does not behave like a particle, like a wave, or like a "combination" of wave-and-particle. Its type of behavior depends on the situation; during interaction with the slits an electron behaves exactly as if it was a wave, and during interaction with the wall an electron behaves exactly as if it was a particle.

To describe the behavior of matter (or light) we use either a wave-explanation or a particle-explanation, depending on the situation. The wave and particle aspects are *complementary* because both are needed to reach a complete understanding.

The usual reaction to wave-particle duality is amazement-and-confusion. Why? Because all of your experience has been with things that act like particles, or like waves, but never like "both". There is no familiar object or phenomenon that can serve as a total analogy. To understand electrons or other wave-particles you must accept this fact: pictures and descriptions that are adequate for everyday experience may not be adequate for areas beyond everyday experience. When you consider that a tennis ball has 10^{32} times more mass than an electron, the fact that their behavior isn't totally analogous shouldn't be too surprising!

The same kind of wave-particle duality occurs for electrons (or other types of matter: neutrons, protons, atoms,...) and photons. To understand this dual nature, you must have imagination and a freedom from preconceived bias. In Chapter 6 of "The Character of Physical Law", Nobel Prize winning physicist Richard Feynman does an excellent analysis of the double-slit experiment, and offers this advice:

> Now we know how the electrons and light behave. But what can I call it? If I say they behave like particles I give the wrong impression; also if I say they behave like waves. They behave in their own inimitable way, which technically could be called a quantum mechanical way. They behave in a way that is like nothing that you have ever seen before. ... Our imagination is stretched to the utmost, not, as in fiction, to imagine things which are not really there, but just to comprehend those things which *are* there. ... It will be difficult. But the difficulty really is psychological and exists in the perpetual torment that results from your saying to yourself, "But how can it be like that?" which is a reflection of uncontrolled but utterly vain desire to see it in terms of something familiar. I *will not* describe it in terms of an analogy with something familiar; I will simply describe it. ... Do not keep saying to yourself, if you can possibly avoid it, "But how can it be like that?"... Nobody knows how it can be like that. {excerpts from pages 127-129}

And we should be thankful it is "like that" because, as explained in Section 17.3, this strange wave-particle duality is necessary for atomic stability and for life.

17.3 Quantum Mechanics

Here is a brief history of quantum mechanics:

In 1900, Max Planck discovered that the properties of blackbody radiation can be described mathematically by assuming that molecules only vibrate with certain amounts of energy; they cannot have an energy between these "allowed amounts". The idea of *quantized* energy was a radical departure from classical physics, which predicts continuous energy levels that can have any value. {This analogy may help you understand the difference: on a continuous ramp ( ) a block can have any value of potential energy but on quantized stairs ( ) its potential energy is limited to certain values.}

In 1905, Albert Einstein reasoned that if molecular vibrations are quantized (with energy assumed by Planck to be multiples of hf: $E_{molecule} = n\,h\,f_{molecular\ vibration}$), then to conserve energy the light caused by these vibrations must also be quantized, and is emitted in light-units that each have an energy of $E_{photon} = h f_{photon\ vibration}$. The *wave-particle duality* of photons is discussed in Section 17.1.

In 1911, Ernest Rutherford proposed the *nuclear* model of the atom, with all of the atom's positive charge and almost all of its mass concentrated in a tiny *nucleus* at the center of the atom. The rest of the atomic volume is "empty space" that is occupied by tiny, lightweight, rapidly moving electrons.

In 1913, Niels Bohr developed a "quantum model" of the atom in an attempt to explain the quantized emission (and absorption) of light by hydrogen atoms.

In 1923, Louis DeBroglie extended the idea of wave-particle duality to include particles that have mass. This is discussed in Section 17.2.

In 1925, Erwin Schrodinger and Werner Heisenberg independently developed two different (but mathematically equivalent) formulations of *quantum mechanics.*

Within a few years, scientists had used this new theory to help explain a variety of physical phenomena, including the details of atomic and molecular spectra, the formation of molecules from atoms, the periodic table of chemistry, and more. This process has continued until now, as scientists look for ways to modify quantum theory and extend it into new areas of nature.

Wave Equations

As discussed in Section 9.2, the superposition of waves moving back and forth on a guitar string produces *standing waves* with quantized frequencies; the string can only vibrate with certain frequencies. In a similar way, an electron moving in an atom forms a standing wave, which leads to quantization of the electron's energy.

A string can vibrate in many standing-wave modes simultaneously. An electron within an atom has many standing-wave modes available (these modes are called *orbitals)* but it can only exist in one mode at a time==[is this correct?]. When an electron changes from one wave-mode to another, light can be emitted or absorbed; this is what produces atomic and molecular spectra.

Equations can be written for many types of waves: water, string, sound, light, matter,... In 1925 Erwin Schrodinger wrote the equation for an electron in an atom, taking into account factors like electrical attraction between the electron and nuclear protons. The solution of this equation gives valuable information about the atomic electron, including its energy, angular momentum, and probable location.

Quantum Mechanics and Probability

Quantum mechanics makes three kinds of predictions; it 1) predicts exact values for some quantities [like angular momentum and energy level for atomic electrons], 2) makes probability-predictions for some quantities, and 3) answers some questions with "I don't know" or "I don't think it is possible for anyone to ever discover the answer to your question".

The last two categories require some explanation.

Classical physics makes definite predictions about motion. For example, in Problem 2-E it predicts the path followed by the The Human Cannonball and the spot where he dives into the whipped cream. But if quantum mechanics is asked to describe the motion of an electron in a double slit experiment, it doesn't try to predict the electron's path or screen-hitting spot. But it can predict the probability that an electron will hit a certain location on the screen, and it correctly predicts the pattern that is formed when a large number of electrons hit the screen. {This is analogous to predicting the results of rolling two dice. We can predict probabilities (there is a 1/36 chance of getting "2", a 2/36 chance of getting "3", and so on) and the probable distribution of results after 1000 throws, but unless the dice are "fixed" there is no way to predict with certainty the result of any individual dice-roll. Section 17.92 discusses the quantum mechanics *wavefunction* "Ψ" and how Ψ^2 can be used to predict the probability of finding an electron at a certain location.}

If you ask quantum mechanics to trace the path of an electron as it moves around inside a hydrogen atom, the theory says "I'm sorry, I can't do that". But this is certainly better than giving a definite answer, like Bohr's *planetary model* with an electron orbiting around the nucleus, that is wrong.

Some philosophers and scientists don't think quantum mechanics is a complete-and-satisfactory theory because it answers some questions with probabilies or with "I don't know". But most scientists think probability-statements are necessary because, as discussed in Section 17.4, there seem to be limitations on "what we can know about how things behave on the microscopic level". {Einstein's "God does not play dice" criticisms of quantum mechanics are discussed in Problem 17-#.}

Most quantum mechanics predictions that have been checked by experiment have turned out to be correct. And the rare failures have inspired modifications that improved and expanded the theory. Scientists generally accept quantum mechanics (and its variations) as a valid theory that can help us understand the fundamental processes of nature.

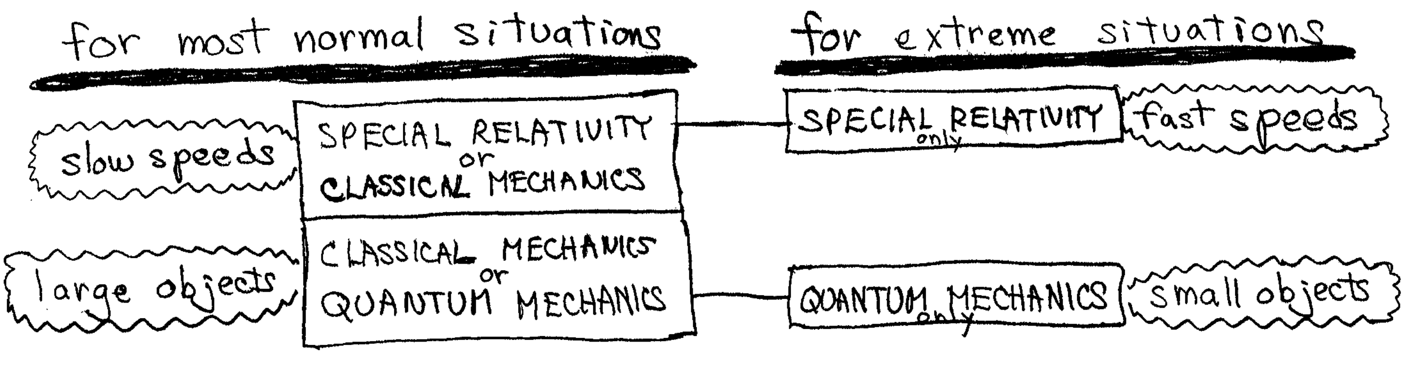
Chapter 16 and Section 17.2 emphasize that you must "stretch your imagination" to understand the behavior of nature in extreme situations, for objects that are very fast or very small. But it is also important to recognize the limits of strangeness; in everyday situations, quantum mechanics and relativity both predict the "normal" behavior that experience has taught us to expect.

For example, a rocket at 24300 miles/hour is fast by normal standards, but slow compared with the speed of light. For this rocket, most relativistic calculations differ from those of classical mechanics by a factor of only $1/\sqrt{1-v^2/c^2} = 1.0000000007$, so the two theories predict almost identical results.

And quantum effects are significant only for extremely small *microscopic* objects like electrons, protons, neutrons and atoms. For large *macroscopic* objects that contain a huge number of atoms, most quantum effects are negligible; a tiny 1 mm grain of sand traveling at 1 mile/hour doesn't have much momentum, but its deBroglie wavelength ($\lambda = h/mv$) is about 10^{-25} meter, less than a million millionth the size of a hydrogen atom. Even the smallest 1-celled animal, too small to be seen without a microscope, is considered "large" by quantum mechanics standards. {Problem 17-# shows how to calculate quantum effects for typical microscopic and macroscopic objects.}

One way to evaluate a theory is the *correspondence principle:* if a new theory is to be judged "satisfactory" it must be able to correctly account for the experimentally verified results of older theories. Do you see why quantum mechanics and special relativity pass this test?

The diagram below summarizes the *range of applicability* for classical and modern theories. For slow speeds either relativity or classical mechanics can be used, but for fast speeds you can only use relativity. Similarly, classical mechanics works well for large macroscopic-level objects, but fails for small microscopic-level objects, while quantum mechanics gives correct results for both levels.



When it is acceptable — for most everyday events that involve relatively slow large objects — it is usually easier (and more intuitive) to use classical mechanics than the more complex methods of quantum mechanics or relativity.

Energy Quantization and the Existence of Life

When you first study quantum mechanics ideas [that an atom is mostly empty space, and all matter has wave-properties] it might seem that matter is not very substantial or reliable. But the strange wave-nature of electrons is what causes energy quantization, and this in turn produces the things we consider to be normal, the things that allow life. In the following passage, from page 101 of "The History of Quantum Mechanics", Victor Guillemin describes what would happen if Planck's constant was zero, which would mean that energy was not quantized:

> ... the deterministic laws of classical mechanics would be universally valid, a highly desirable state of affairs, so it would seem.
>
> However, if Planck's constant were zero, there would have been no Planck, and indeed no rational beings, or any forms of life, for it is quantization that accounts for the existence of stability and organization in the atomic substratum of the universe. Because the energy content of atoms is restricted to certain discrete values (page 57), an assault of considerable energy is needed to jolt them out of their normal state, and afterward they return quickly and precisely to normal. Without quantization there could be no definite normal state. Any electronic configuration whatsoever would be possible, and the slightest disturbance could alter this configuration permanently. Atoms would have no stable and specific properties. There would be no well-defined organization of atoms into molecules or of molecules into large structures. The universe would be a formless and meaningless blob without history, plan or purpose. In our present earthly environment quantization alone makes atoms act — to use Newton's words — like the "solid, massy, hard, impenetrable particles" formed by God in the beginning "that nature may be lasting".

This is a good description of why quantization is necessary for life. But to make a non-quantum universe seem even less desirable, think about what would happen to protons (with positive electric charge) and electrons (with negative charge). Without quantization they would attract each other until they came into contact and formed ± clumps that would be useless as building blocks for life. { Problem 17-# shows why the wave-nature of electrons prevents the formation of such ± clumps. }

17.4 The Uncertainty Principle and Critical Thinking

To find the speed of a tennis ball in a dark room we could take two flashbulb photographs, measure the distance "Δx" the ball travels between the photos, the time "Δt" between them, and calculate "$\Delta x / \Delta t = v$". When we take a photograph some flashbulb photons hit the ball (which reflects them back to the camera film) and a tiny amount of photon momentum is transferred to the ball. But the ball's mass is so large that this momentum doesn't have a significant effect on the ball's motion. If we take three photographs of the ball, and Δt between the photos is very small [so the effects of gravity & air resistance are negligible], the ball's positions form an almost-straight line (• • •), and calculation of $\Delta x/\Delta t$ for the 1-to-2 and 2-to-3 intervals gives almost almost exactly the same velocity.

But if we use this method to measure the speed of an electron, interaction between a photon and the tiny electron will change the electron's motion in a significant and unpredictable way. Three quick photos will probably not form a line [instead, we might get a result like · . ·]. The $\Delta x/\Delta t$ velocity calculated for 1-to-2 and 2-to-3 are different because photon/electron interaction during the second photograph causes the electron's after-the-photo velocity to be different than its before-the-photo velocity. For this same reason we cannot predict the 3-to-4 velocity with much confidence, so we say that there is an "uncertainty" in our knowledge of the electron's velocity after the third photograph. We know what the electron has done (1-to-2 and 2-to-3) but we cannot predict with certainty what it will do next (3-to-4).

During any *act of observation* there is unavoidable interaction between the observing-instrument and thing-being-observed (a photon and electron, respectively, in the example above). Wave-particle duality produces energy quantization, so the changes that occur during an observation-interaction cannot be reduced below a certain level. This causes a "natural limitation" on the precision of measurements, a limitation that is called the *uncertainty principle.* It can be expressed as

$$\Delta x \; \Delta p_x \; \geq \; \frac{h}{2\pi}$$

where Δx is the "uncertainty" in our measurement of the object's x-position
{ notice that "Δ" does not have its usual meaning of "change" } ,
Δp_x is the uncertainty in measuring the object's momentum in the x-direction,
$\geq$ means "is either greater than or equal to",
and **h** is Planck's constant (it is the same h that is in Section 7.1's "$E_{photon} = hf$").

There are several equivalent ways to express the uncertainty principle. Another formulation is $\Delta E \; \Delta t \geq h/2\pi$, where ΔE and Δt are the uncertainties in energy and time measurements.

==[unc.pr. is also important for non-measurement situations (see later in 17.4)]

These limitations are imposed by nature, not by a lack of technology or cleverness. No matter how carefully we make measuring instruments and plan experiments, we cannot make measurements that are more accurate than is allowed by the uncertainty principle.

For example, if we use a single photon to examine an electron, diffraction effects (these may be discussed in your textbook's "optics chapter") limit how precisely we can measure the electron's position; to get a small Δx, we must use a photon with short wavelength. But a small-λ photon has large energy and momentum, because $p = h/\lambda$, so the interaction causes a large Δp_x for the electron. Do you see that the smaller we make Δx (by using a small λ), the larger Δp_x becomes? No matter what strategy or equipment we use, we can never reduce the product of Δx and Δp_x below $h/2\pi$. {But this product can be larger than $h/2\pi$, if an experiment isn't "done perfectly".}

Quantum Mechanics and Critical Thinking

The Chapter 17 introduction states that to understand quantum mechanics you must be freely imaginative without getting silly. The end of Section 17.2 encouraged you to drop preconceived ideas about the way nature "should be" and use your imagination to understand the way it "really is".

Now it is time to establish boundaries. Yes, wave-particle duality is strange, but there are limits to its strangeness. Some "pop physics" books (with titles that include mysticical-sounding words like "Tao" or "Wu Li") seem to have gone beyond the boundary of scientific validity. In the following discussion these are referred to collectively as *mystical physics* (MP) books. Let's compare some of their claims with sound scientific theory.

MP books contain a number of logical errors, including: 1) a wrong definition of *observation,* 2) sloppy use of language analogies, 3) confusion of microscopic and macroscopic "levels", 4) not explaining the *solipsism* that is the main philosophical foundation for their arguments, and 5) mixing science with speculation.

OBSERVATION: As it is used in the uncertainty principle, *act of observation* refers to a direct physical interaction with the object being observed. Earlier in this section we found that interaction with a photon will change an electron's momentum. And Section 17.2 describes how interaction with a photon (which is used to determine the electron's location) destroys an electron's double-slit interference pattern. In these examples it is a photon that does the "observing"; it is definitely not, as is often implied or stated in MP books, the "consciousness of a human observer".

SLOPPY USE OF LANGUAGE-ANALOGY: MP books sometimes use sloppy logic by comparing occasional similarities in the language used by physicists and mystics, then implying that there is some deeply rooted connection between them. In doing this, they ignore the fact that physicists may use a phrase to mean one thing while a mystic uses a similar phrase to mean something entirely different.

CONFUSION OF LEVELS: Section 17.2 emphasized that *macroscopic-level* ideas are not totally adequate for interpreting *microscopic-level* events. MP books make the reverse mistake, by assuming that quantum descriptions of microscopic events (involving electrons,...) are applicable to everyday macroscopic events.

MP books describe the modern physics view of nature [matter is energy with wave-like properties, most of the volume of an atom is empty space filled with electron waves, a system is changed by observation,...], then imply that everything is a "semi-real dance of energy waves" that can be shaped by human observers. What they conveniently ignore is the fact that even though quantum mechanics describes subatomic events in a "very strange way", it describes everyday events in a "very normal way". As explained by Guillemin, it is strange microscopic behavior that produces normal macroscopic behavior.

Another MP claim is that the entire universe is one interconnected wave, so each part of it is affected by every other part of it. This is true, but most quantum effects (with the exception of photon travel) are very localized. Consider this analogy: if a grain of sand drops into the Pacific Ocean in California it will theoretically cause a change on the shores of Hawaii, but no practical effect is transmitted to Hawaii because the sand's tiny wave-splash is — like the analogous tiny quantum effects — quickly neutralized by random collisions with other water molecules.

SOLIPSISM is the theory that "nothing is real except me and my experience". Do you think that a forest doesn't exist when you are not there to observe it? If you think the forest (including all trees, bugs, dirt, squirrels,...) really does disappear, then you have a logical basis for believing MP arguments. Because most readers won't accept an argument based on making forests vanish, MP books camouflage their solipsistic foundation with faulty quantum mechanics arguments.

Here is one of them. When an electron passes through double slits, the place where it will hit the screen is not determined until it actually hits the screen. Until then the electron is a wave-function that could hit anywhere, and "all possibilities exist". So far, this is standard science. But MP books claim that the electron is "unreal" until an act of observation (by a human observer, it is implied) "creates the reality", and conclude that "objective reality doesn't exist outside of the mind of the observer". This conclusion is not supported by physics. The idea that "particles are real, but waves are unreal" is pre-1923, not modern. If the wave-particle duality of electrons is accepted, an electron is just as "real" when it is a wave moving toward the screen as when it is a particle hitting the screen. Here are two other errors: 1) our lack of knowledge about its eventual hitting-place doesn't make the electron unreal, and 2) *observation* is (as usual) misdefined — in this experiment a wall, not a human, is the "consciousness" that makes the observation.

Even if there was an element of human participation in this experiment (which there isn't except for designing the equipment and pushing buttons that make it go), it is a rare and artificial situation; 99.99999...% of what happens in the universe does so despite its "lack of being observed by humans". {People do, of course, play an important role in our world. The real effects of human activity are discussed in Problem 17-#.} Every time an electron interacts with another particle, like when two atoms collide with each other inside a squirrel in a forest, an observation-interaction occurs!

SCIENCE AND SPECULATION: MP authors often mix orthodox scientific ideas with personal speculation, without letting the reader know where one ends and the other begins. This tends to confuse and mislead any reader who lacks scientific expertise, especially in quantum mechanics where, as Feynman says, "our imagination is stretched to the utmost". If a reader is not scientifically confident, he is less likely to challenge the logic of a scientist-author "expert". It is especially easy to fool a reader who would really like to have the power to "create his own reality" and is looking for a reason to believe that it can be done.

As explained here, physics doesn't support the "new age mysticism" of MP books. Neither does physics disprove such views; this is discussed in Problem 17-#.

When anyone claims that a particular philosophical viewpoint is supported by science, we should use *critical thinking* to test the claim. This is explored in the last section of the book, Section 20.7 — Creativity, Critical Thinking, and Science.

17.90 Memory-Improving Flash Cards

17.1	Some particle characteristics are __ .	velocity, mass, definite path, count-able, can collide, two cannot occupy same space
	Some wave characteristics are __ .	velocity, frequency, wavelength, amplitude, can occupy same space (superposition)
	Light: classical says __ , 1905 Einstein says __ .	is EM wave only, is wave-particle photons
17.1	Photon energy depends on __ , but not __.	light frequency, light intensity (brightness)
	If __ , photoelectron number depends on __ .	E_{photon} (hf) exceeds W_o , light intensity
17.1	Usually, __ interacts with __ .	one photon, one electron
	Photon energy can be used to __ .	remove photoelectron (W_o) and give it KE
17.2	In __ , __ proposed __ .	1905, Einstein, light wave-particles
	In __ , __ proposed __ .	1923, DeBroglie, matter wave-particles
	In __ , experiments showed __ for __ .	1927, wave interference, matter-particles
17.2	With one slit open, electrons produce __ .	a single-slit diffraction pattern
	With two slits open, electrons produce __ .	a double-slit interference pattern
	Two slits with "observation" produces __ .	two independent single-slit patterns
17.2	An electron passes through two slits __ .	as if it was two electron-waves
	An electron always hits the screen __ .	as a "whole electron" particle
	An electron has __ but not __ .	self-interference, self-repulsion
17.2	__ is analogous to wave-particle duality.	no familiar object or phenomenon
17.3	Planck & Einstein proposed quantized __ .	molecular-vibration energy & photon energy

17.3	Superposition produces __ for string __ .	quantized frequency, standing waves
	Superposition produces __ for electron __ .	quantized energy, standing waves
17.3	A __ can be __ for an electron in an atom, to give information about __ .	wave equation, written and solved energy, angular momentum, location, ...
17.3	In most situations, __ and __ are equivalent.	classical mechanics, quantum mechanics
	Wave-properties are only significant for __ .	atomic-level objects with very small mass
17.3	The __ causes __ of energy, which produces atomic __ and allows the __ .	wave-nature of matter, quantization, stability & characteristics, existence of life
17.3	QM makes 3 kinds of predictions: __ .	exact, probabilistic, I don't know
	An answer of __ is better than __ .	I don't know, an incorrect answer
17.4	The __ states that __ is limited by the __ in addition to practical __ limitations.	uncertainty principle, measurement precision nature of wave-particles, experimental
17.4	This limitation is significant for __ , not __ .	atomic-level particles, everyday objects
17.4	QM observation can be done by __ , not __ .	a photon, wall, atoms,...; human thought
	Despite __ , QM predicts __ behavior.	wave-particle strangeness, normal everyday
	MP is based on __ , the idea that __ .	solipsism, only me & my experience is real
	__ is just as real as __ .	An electron-wave, an electron-particle
	All theories should be checked by __ .	critical thinking (as discussed in 20.7 finale)