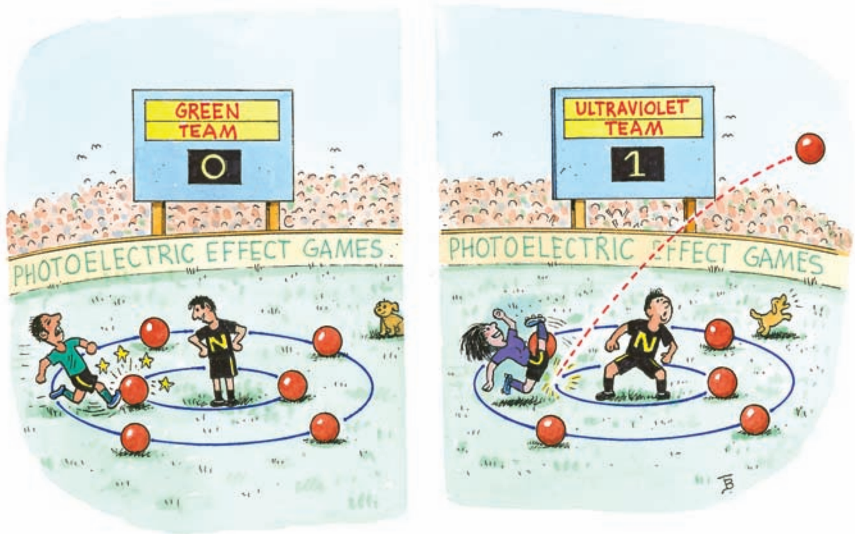
Section 5

Wave-Particle Model of Light: Two Models Are Better Than One!

What Do You See?



Learning Outcomes

In this section, you will

- **Observe** the diffraction of light waves.
- **Observe** the interference of sound waves.
- **Observe** the interference of light waves.
- **Construct** a model of wave interference.
- **Solve** simple problems related to the photoelectric effect.
- **Describe** the wave-particle duality of light.
- **Describe** the wave-particle duality of electrons.

What Do You Think?

Light from the Sun takes eight minutes to reach Earth. Light from the nearest star takes years to reach Earth. Light from another galaxy takes millions of years to reach Earth.

- **When you turn on a lamp and the light travels from the bulb to your book, how long do you think it takes to get there?**
- **How does light travel from one place to another?**

Record your answers to these questions in your *Active Physics* log. Be prepared to discuss your responses with your small group and your class.

Investigate

In *Investigate*, you will observe the wave properties of light by simulating wave motion. You will observe constructive and destructive interference, and diffraction. By investigating Einstein's theory of the photoelectric effect you will learn about the nature of light. Finally, you will also compare the behavior of electrons to the behavior of light.

Part A: Does Light Behave as a Wave?

1. Physics is the art of creating *models* in terms of which scientists try to understand objects and processes in nature. Two important models are *particles* and *waves*. Particles are localized bits of matter, like a ball in flight. Waves spread out like ripples in a pond, even though the water does not move in bulk.

   a) If you write a letter, stuff it into an envelope and mail it to a friend, are you using particle motion or wave motion?

   b) When the crowd at a football game does a “wave” around the stadium, why is it called a “wave”?

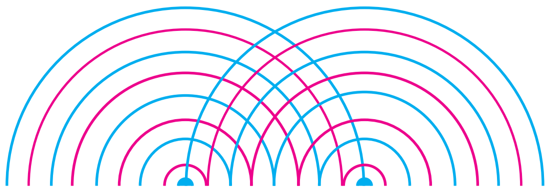
   c) When you listen to music, does the sound travel from the band to your ears as a particle, or as a wave?

   d) In a hailstorm, does the hail come down as particles, or as waves?

   e) Does light from the Sun come to Earth as particles, or as waves?

   From the model of an atom, you have a good idea that most of the mass and all the positive charge are in a central nucleus, and the low-mass, negatively charged electrons orbit the nucleus. To better understand the behavior of the orbiting electrons, you must understand the contrasting properties of waves and particles.

2. The hallmark feature of wave motion is interference. When waves pass by each other, in some locations there are conditions where there is no motion of the medium, whatsoever. In the diagram, source 1 and source 2 interfere with each other and in some locations the waves cancel each other out. If these waves were in water, water waves + water waves would create still water.



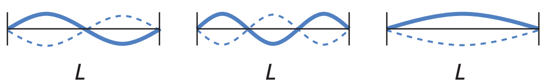
   If sound were a wave, it would mean that sound + sound could equal silence. If light were a wave, it would mean that light + light could create dark.

   Demonstrating interference is definitive evidence of wave phenomena.

   a) For the water waves shown above, the blue circles represent the crests of waves and the red circles represent the troughs of waves. Whenever a crest and a trough meet, the waves cancel. In your log, indicate where the waves would cancel to produce still water.

3. Consider a musical instrument, perhaps a guitar. When a string is plucked, the waves that travel up and down the string are some combination of standing waves that you will now simulate with a giant coiled spring.

   Stretch a coiled spring (or a rope) between you and your lab partner. While one of you holds one end fixed, the other will vibrate the spring. Adjust the *frequency* (number of times per second you shake the coiled spring) until you produce as many patterns as you can. In the diagrams below, L is the length of the coiled spring:



a) In your *Active Physics* log, sketch the standing wave patterns that you were able to make.

b) Identify the parts of the coiled spring that do not move. The wave travels away from the person vibrating the spring and is then reflected from the other end so that the wave travels back toward that person. You have two waves interfering. The points where the spring does not move are called *nodes*. You conclude that the coiled spring waves are waves because they can interfere with one another and form nodes.

4. Hit a tuning fork gently against a rubber stand. Place the tuning fork near your ear. Slowly rotate the tuning fork so that one prong gets closer to the ear while the other gets further away. Listen carefully to the volume of the sound.

Do not touch the vibrating tuning fork to your skin, especially near your ear.

a) Record your observations in your log.

A tuning fork produces identical sounds from each prong. At one orientation from the prongs to your eardrum, you heard a loud sound. This loud sound was *constructive interference*. When the orientation from the prongs to your ear was different, the sound diminished.

The interference of waves is another property of wave behavior. If you are unsure that you observed the interference of sound, listen to the tuning fork again. Because sound from one prong of the tuning fork can interfere with the prong of the other tuning fork and produce areas of very low sound (nodes), you conclude that sound is exhibiting a wave phenomenon.

5. Is light a wave? Two properties that define waves are interference and diffraction. The process of light bending and spreading out as it squeezes through a small opening is called *diffraction*. Light bending around an edge is also referred to as diffraction. Here you will use a laser. Shine a laser beam against a wall as shown on the next page.

Never look directly at a laser beam or shine a laser beam into someone's eyes. Always work above the plane of the beam and beware of reflections from shiny surfaces.

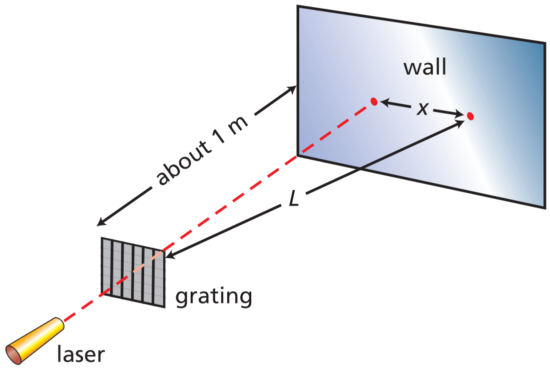
a) Place a piece of paper on the wall, and trace the beam onto the piece of paper to measure its thickness. Record your measurement.

b) Place a single narrow slit in front of the beam. Measure and record the thickness of the beam again.

c) Place a thinner slit in front of the beam. Measure and record the thickness a final time.

d) What happens to the width of the laser beam as it passes through a smaller and smaller opening?

Diffraction is one of the properties that all waves exhibit, including water waves and sound waves. Diffraction of light seems to suggest that light is a wave.



6. If you can find an instance where light plus light produces no light (a node), you will have evidence that light is a wave. Shine a laser beam through two slits or a diffraction grating made up of many slits. Direct the beam at a distant wall. Your teacher may do this as a demonstration. Observe the pattern of the light on the wall.

   a) Record your observations in your log.

   b) From your observations, what can you conclude about the ability of light to interfere? Are there places on the wall where there is no light? Explain.

   On the distant wall, you will see places where the light from neighboring slits interferes constructively (there is maximum light) and places where the light interferes destructively (there is little or no light). These places of darkness are evidence of the interference of light and would seem to suggest that light behaves like a wave.

Part B: The Photoelectric Effect

Now that you have found that light behaves like a wave you can turn to the puzzle that Einstein solved. This puzzle, the *photoelectric effect*, has to do with the behavior of light shining on metal and freeing electrons from the metal. You make use of this effect in everyday life: solar-powered calculators, solar collectors, photogates for electronic timers, digital cameras, television remote controls, door-opener sensors, etc. This idea is illustrated with an analogy as follows:

1. A vending machine sells potato chips. The machine is not able to add coins.

   Suppose a bag of potato chips costs 10¢.

   - If you place 10¢ in the machine, a bag of potato chips comes out.
   - If you place 5¢ in the machine, your 5¢ is returned.
   - If you place 25¢ in the machine, a bag of potato chips comes out and you get 15¢ in change.
   - If you place 2 nickels in the machine, the 2 nickels are returned (the machine cannot add coins).

   a) What would happen if you placed a 50-cent piece in the machine?

   b) What would happen if you placed 20 pennies in the machine?

   c) What would happen if you placed a $1.00 coin in the machine?

   d) An equation that could describe the behavior of the machine would be:

   money inserted = returned money + cost of chips.

   Does this equation work for the examples above?

   This vending machine can be used to explain the photoelectric effect. In the photoelectric effect, light hits a metal surface and an electron may be freed. In the term photoelectric, "photo" is for the light and "electric" is for the freed electron.

   In the photoelectric effect:

   - The frequencies of light are like the coins placed in the chip machine. Some frequencies of light will never free electrons, regardless of how much light there is. This phenomenon is similar to having lots of pennies or nickels to place in the vending machine.
   - Frequencies of light above a certain minimum frequency, called the threshold frequency, will free electrons. This phenomenon is similar to requiring at least a dime to get a bag of chips.

- Also, the brighter the light, above the threshold frequency, the more electrons freed. This phenomenon is similar to having lots of dimes to place in the chip machine and more than one bag of chips in the machine.
- Some frequencies of light will free electrons and give them lots of kinetic energy. This phenomenon is similar to quarters being placed in the chip machine. Each quarter gets a bag of chips and some change.

Einstein was able to explain the experimental observations of the photoelectric effect by assuming that light collided with the metal as particles of light. Each particle or *photon* of light would have a specific energy.

A metal may require a minimum energy of 10 eV to free a single electron. The minimum energy needed to remove an electron from an atom is called the *work function*. If each photon of light has less than 10 eV of energy, then no electrons will be freed, no matter how many photons are in the light beam. (This situation is similar to requiring 10¢ to get a bag of chips. No matter how many nickels or pennies you have, you will not be able to get chips.) If the photon of light has exactly 10 eV of energy, then one electron will be released. If the photon of light has 25 eV of energy, then one electron will be released and it will leave with 15 eV of kinetic energy.

2. This process can be written as an equation, very similar to the equation for the chips:

energy of light = (kinetic energy of freed electron) + (work function).

Or, in symbols,

$$E_{\text{light}} = KE_{\text{electron}} + w_o$$

a) If the work function of a metal were 7 eV, what would happen to the electrons in that metal if the photons of light hitting it had an energy of 12 eV?

b) If the work function of a metal were 12 eV, what would happen if the photons of light had an energy of 12 eV?

c) If the work function of a metal were 7 eV, what would happen if the photons of light had an energy of 18 eV?

d) If the work function of a metal were 9 eV, what would happen if the photons of light had an energy of 12 eV?

e) If the work function of a metal were 14 eV, what would happen if the photons of light had an energy of 12 eV?

3. The energy of light can be determined by its frequency, wavelength or color. Red light comes in low-energy packets of *photons*, violet light comes in high-energy packets and ultraviolet light comes in even higher-energy packets. The equation is

$$E = hf$$

where E is the energy of the photon of light,

h is a constant, called Planck's constant $\left(6.63 \times 10^{-34}\ \text{J}\cdot\text{s}\right)$, and

f is the frequency of light.

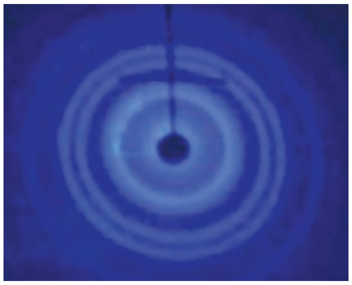
a) Explain why shining a very bright red light may not free an electron from a metal surface, while shining a very dim violet light may free many electrons.

Part C: Matter Waves – The Nature of Electrons

1. Recall that light shows both particle-like and wave-like behavior, and which one it shows depends on the experiment you are doing with light. Louis de Broglie, a French physicist, had a striking thought: Perhaps if two models are necessary for light, two models are also necessary for electrons. Electrons hit screens as if they are particles. Could they go through slits and exhibit interference?

   If nature takes this suggestion seriously, then when you fire a beam of electrons through a double slit, you should see an interference pattern identical to that made by light of the same wavelength.

   An experiment to test this idea with electron beams was first done in 1929 and confirmed the de Broglie hypothesis! The results are shown in the diagram.



   a) Sketch the diagram of the experimental result in your notebook. Indicate in your drawing that the dark positions are where no electrons hit the screen. These are nodes.

   To create this experimental result, electrons traveled through a metal crystal of atoms. The spaces between the atoms served as "slits" for the electron beam. The electrons set up a diffraction/interference pattern on the screen. This is evidence that electrons can exhibit wave characteristics.

   In summary, you have an astonishing result: For some situations, the electron can be described only in terms of waves; for others you have to describe it in terms of particles.

2. Consider, for example, an electron not in an atom, but just bouncing back and forth between the walls of a box. The electron's de Broglie waves in this situation look just like the standing waves on the coiled spring and like the standing waves on a guitar string.

   a) Keeping in mind the guitar string concept, draw two additional waves that could fit in the box.

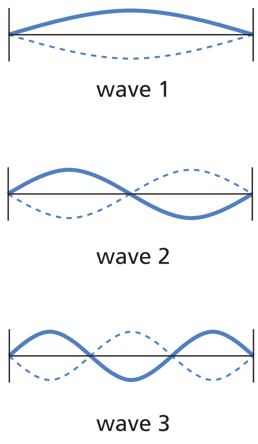
   b) Identify where the nodes are for each of the standing waves.

3. The de Broglie wave determines the location of the electron in the box. If you imagine the standing wave in the box, the electron will most often be found where the peaks (*antinodes*) of the wave are located. The electron will never be found at the positions where the nodes are located.

   a) In the first diagram on the next page, you expect that the electron will usually be found somewhere near the middle of the box because that is where the antinode is. The electron is never found at the edges of the box because there are nodes at both ends. Copy this diagram into your log and mark the spot where the electron is most likely to be found.

b) In the second diagram, you expect that the electron will usually be found on the left side of the box or on the right side of the box. The electron will never be found in the middle of the box because a node exists in the middle of the box. Copy this diagram into your log, and mark the spot where the electron is most likely to be found.

c) Indicate where it is likely to find the third electron, and where you would never find the third electron.



Physics Talk

MODELS

The Dilemma of Light

The first set of experiments showed that light can diffract and can interfere. The experiments are evidence that light has **wave** characteristics. Einstein's explanation of the **photoelectric effect** also provides evidence that light behaves like a **particle**. In the photoelectric effect the emission of electrons from certain metals takes place when light (electromagnetic radiation) of certain frequencies shines on the metals.

You may want to ask, "What is light, wave or particle?" But that is not the question. Particles and waves are **models** that originated with the ways you think about things. Particles describe localized bits of matter and waves describe transfer of energy without the transfer of matter. These models are a conceptual representation of a process, system, or object. However, neither of these models alone can describe everything that light does. You need both models, using the one or using the other, depending on the situation, to describe all that light can do! For interference, a wave model of light makes sense of our experience; but for the photoelectric effect, a particle model is a better fit.

When you see light rays piercing through the clouds or a laser beam in a music show, you recognize that light travels in straight lines. In this section, you found out that light may also spread out as it squeezes through a small opening.

The process of light spreading out as it squeezes through a small opening is called **diffraction**. Light bending around an edge is also referred to as diffraction. Diffraction is one of the properties that water waves and sound waves exhibit. The phenomenon of diffraction leads toward the conclusion that light might also behave as a wave.

Physics Words

wave: a model that describes transfer of energy without the transfer of matter.

photoelectric effect: the emission of electrons from certain metals when light (electromagnetic radiation) of certain frequencies shines on the metals.

particle: a model that describes localized bits of matter.

model: a conceptual representation of a process, system, or object.

diffraction: the ability of a wave to spread out as it emerges from an opening or moves beyond an obstruction.

You also explored another property of water and sound waves. When water waves meet, they interfere with one another. **Constructive interference** occurs when the crests of a wave meet the crests of the second wave, and there is lots of movement of the water. **Destructive interference** occurs when the troughs of one wave meet the crests of the other wave and the water remains still.

You used a tuning fork to investigate if sound waves also interfere. A tuning fork produces identical sounds from each prong. At one orientation from the prongs to your eardrum, you heard a loud sound. This loud sound was constructive interference. When the orientation from the prongs to your ear was different, the sound diminished. The sound from one source can meet with the sound from another source and produce silence! The interference of waves is another property of wave behavior.

If light behaves like a wave, then it, too, must show interference. When you shone a laser beam through two slits onto a distant wall, you saw an interference pattern. There were places where the light from neighboring slits interfered constructively (there was maximum light) and places where the light interfered destructively (there was little or no light). Evidence of the interference of light would seem to prove that light behaves like a wave. The colors you see when light reflects off a CD or soap bubble are interference effects.

After you found that light behaves like a wave, you turned to the puzzle of the twentieth century that Einstein solved. The puzzle had to do with the behavior of light when it freed an electron from a metal. In the photoelectric effect, when beams of light shine on metals, some **wavelengths** (and **frequencies**) of light will always free electrons, while other wavelengths (and frequencies) will never free electrons. For some materials, light of high frequency (ultraviolet light) frees electrons and gives them kinetic energy. Light of low frequency (red light) is not able to free any electrons. Einstein developed a model of the process

Physics Words

constructive interference: the result of adding waves crest-to-crest to produce a wave with a greater amplitude.

destructive interference: the result of adding waves crest-to-trough to produce a wave with a decreased amplitude.

wavelength: crest-to-crest distance in a wave.

frequency: number of cycles per second in the wave's vibration.

as a collision between a particle of light (a photon) and an electron. By applying conservation of energy to that process, he derived the following equation for the photoelectric effect in 1905:

$$hf = KE_{\text{electron}} + w_o$$

The energy of the light-as-particle is equal to *hf* where *h* is Planck's constant $(6.63 \times 10^{-34}\,\text{J}\bullet\text{s})$ and *f* is the frequency of the corresponding light-as-wave. Einstein won the Nobel Prize in physics for his concept of photons (not his theory of relativity). A **photon** was described as a particle of electromagnetic radiation, a quantum of light energy.

Comparing the many behaviors of light, the extraordinary conclusion is that light sometimes behaves as a particle (the photoelectric effect) and sometimes behaves like a wave (diffraction and interference effects).

Physics Words

photon: a particle of electromagnetic radiation; a quantum of light energy.

wave-particle duality: the use of two models of light to explain the behavior of light—both as a particle and as a wave.

Developing the Wave-Particle Model of Electrons

Now consider the behavior of electrons. Electrons hit the front of your TV screen and make a temporary mark. Electrons have a mass $(9.1 \times 10^{-31}\,\text{kg})$ and a charge $(1.6 \times 10^{-19}\,\text{C})$. Electrons behave like particles. Electrons can also interfere! Clinton Davisson and Lester Germer demonstrated this by shooting electrons through a metal crystal foil. They observed some locations on a distant screen where many electrons landed and other locations where no electrons landed. This pattern of locations was identical to an interference pattern formed by light, and was explained as an interference effect of electrons. Electrons, like light, can sometimes behave like a particle and sometimes behave like a wave.

What are you to make of electrons as chunks of matter with a mass and charge, and electrons as standing waves? You need both the wave and particle languages to fully explain the electron. Whatever the electron is, neither a particle concept nor a wave concept can describe everything it does. However, the concept of **wave-particle duality** uses two models to describe the behavior of light—both as a particle and as a wave. A key to understanding wave-particle duality is to recognize that waves and particles are models. Particles and waves are conceptual representations of real things based on experience with familiar objects such as water and billiard balls. These models describe particles as localized bits of matter and waves as a transfer of energy but not matter. The real nature of an electron lies well beyond the range of immediate experience.

Electrons move about the nucleus and in the particle view they move in a restricted orbit. However, the models for the structure of the atom include a wave model. An electron may move about the nucleus, but it is not as simple as being restricted to precise orbits. An electron has wave properties. The best one can do is to describe the probability of where an electron can be found and where it cannot be found.

In wave language, Bohr's orbits correspond to locations where an electron in three dimensions is most likely to be found. Each orbit corresponds to the most probable location for an electron of specific energy. The equation that describes an electron wave and its corresponding probabilities is the Schrödinger equation. Erwin Schrödinger (1887–1961) was an Austrian physicist who shared a 1933 Nobel Prize for new formulations of the atomic theory.

Schrödinger's equation gives calculated results for the de Broglie waves that agree with experiment far more accurately than Bohr's. The subatomic world is not the like the everyday world you experience. The "everyday" view of the world makes common sense, but does not provide a complete picture of everything. The subatomic world lies far outside everyday experience and therefore appears to contradict common sense, but the models that have been developed of that subatomic world give correct answers. All the numerical results from predictions based on the Schrödinger model are more accurate than Bohr's. It is a dilemma. Do you go with the theory that gives right predictions but sometimes runs counter to common sense or go with common sense that does not give accurate experimental results? What do you think?

Erwin Schrödinger was a Nobel Prize winning physicist.

Checking Up

1. What is the dilemma of light? Explain why two models are used to explain the behavior of light.
2. Explain the difference between constructive and destructive interference.
3. How is an electron similar to light?

Active Physics Plus

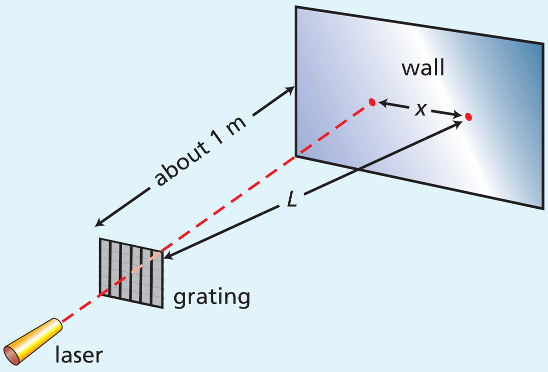
+Math	+Depth	+Concepts	+Exploration
◆			◆◆

The Wavelength of Light

1. If light behaves like a wave, then you can use the interference of light to measure the wavelength of light. Mount a diffraction grating in the path of a laser beam. Mount a screen at least one meter away from the grating as was shown on the next page. Observe the pattern of spots on the screen.

   a) Measure and record the separation between one spot and the next, x.

   b) Measure and record the perpendicular distance from the grating to the screen, L.



c) Record the spacing between the lines of the grating, *d*. You can use the spacing given by the manufacturer.

From your measurements, find the wavelength of the light. You will use the following equation:

$$\lambda = xd/L$$

where λ is the wavelength of laser light,

x is the separation between the spots,

d is the spacing between lines in the grating.

L is the perpendicular distance from the grating to the central spot on the screen,

Show your calculations in your log.

The Photoelectric Effect

1. In order to study the photoelectric effect, a student will vary the frequency of the light incident on a metal. For each frequency of light, the student recorded the kinetic energy (*KE*) of the ejected electron. The data in the chart below gives the result of one experiment.

   a) Graph the results of the data set with the *KE* of the electron on the *y*-axis and the frequency of the incoming light on the *x*-axis.

Frequency of light (Hz) ($\times 10^{14}$)	Maximum kinetic energy of the electron (eV)
6.32	0.15
6.67	0.30
7.06	0.45
7.50	0.65

   b) By extending your graph, determine the threshold frequency of this material (i.e., the frequency of light that will free an electron with a *KE* of 0 eV).

   c) What is the significance of the slope of the graph?

What Do You Think Now?

At the beginning of the section you were asked the following:

- **When you turn on a lamp and the light travels from the bulb to your book, how long do you think it takes to get there?**
- **How does light travel from one place to another?**

Now that you know more about light, how would you describe its nature? What evidence do you have that light behaves like a wave? How would you explain that light behaves like a particle?

Physics
Essential Questions

What does it mean?

Why can't you say that "the electron is a particle, at all times, and in all circumstances?" Why can't you say "light is a wave, at all times, and in all circumstances?"

How do you know?

What evidence exists that sometimes light behaves like a wave, but sometimes light behaves like a particle?

Why do you believe?

Connects with Other Physics Content	Fits with Big Ideas in Science	Meets Physics Requirements
Nature of matter	* Models	Experimental evidence is consistent with models and theories

* Physicists use models to explain observations of the world. The simple models of particle or wave were not sufficient to explain the behavior of light. What did physicists do when their models were not satisfactory?

Why should you care?

The structure of the atom includes an electron that exhibits both wave and particle characteristics. How can you incorporate the complex nature of electrons in your museum exhibit?

Reflecting on the Section and the Challenge

In this section, you found out that light behaves like a particle in the photoelectric effect and like a wave in diffraction and interference effects. Similarly, electrons behave like particles when they hit a screen and like waves when they move about the nucleus. The atomic model has grown more complex and because of that you have seen that the simple models have limitations. Your museum exhibit may require you to explain those limitations and why more than one model for light or electrons, and for the atom itself, is necessary. Creativity and your imagination will be required to make this part of your exhibit interactive and scientifically correct.

Physics to Go

1. Describe two differences between particles and waves.
2. Someone decides that a laser beam is not thin enough. They decide to pass the beam through a very thin slit to slim it down. Will this work? Explain.
3. What was the principal understanding that emerged from Einstein's explanation of the photoelectric effect?

4. Why don't you see in everyday life the "wave nature" of a baseball? The mass of a baseball is 0.145 kg. If the baseball moves at $30\ \text{m/s}$, compute its de Broglie wavelength ($\lambda = h/mv$). Since diffraction and interference, to be noticeable, requires slit dimensions that are roughly the same size as the wavelength, is "baseball diffraction" going to be observable?

5. In the photoelectric effect, a 10 eV photon of light frees an electron from a metal with a work function of 4.2 eV. What is the energy of the emitted electron?

6. The equation for the photoelectric effect is:

$$KE_{\text{electron}} = E_{\text{light}} - w_o$$

Explain what each of the terms in the equation represent.

7. In designing your museum exhibit, what might be a creative way to show the unusual behavior of an electron in an atom?

8. For your museum exhibit or perhaps a product for the museum store, can you invent a photoelectric-effect bank? How would it work?

9. The great physicist Niels Bohr once suggested that there are two kinds of truth: simple truth, and deep truth. The opposite of a simple truth is false, but the opposite of a deep truth is also true. Taking Bohr's definitions of simple and deep truth, is the wave model of light and the particle model of the electron, "simple" or "deep" truths?

10. In the *Physics Talk* section you were asked what you would do: Go with a theory that gives all the right predictions but runs counter to your common sense OR go with your common sense that does not yield accurate experimental results. Explain your answer to this question and the reasoning you used. (Consider that common sense is based on experience.)

11. Active Physics Plus A certain metal has a work function of 1.8 eV, and the wavelength of its threshold frequency is 700 nm. (A nanometer [nm] is $10^{-9}\ \text{m}$.) Light shines on the metal, delivering energy at the rate of $0.01\ \text{eV/s}$.

   a) Ignore for a moment the photoelectric effect. Supposing the electron could "soak up" and save all this energy until it could be liberated, how long would it take to liberate the electron?

   b) Now recall the existence of the photoelectric effect. Will an electron be emitted if more energy per second is delivered to the metal but the light's wavelength is greater than 700 nm?

   c) Will an electron be emitted if less energy per second is delivered to the metal but the light's wavelength is less than 700 nm?

   d) Suppose you do the experiment with light at 690 nm, but with an energy delivery rate of $1.8\ \text{eV/s}$. If an electron is emitted in a millionth of a second, what does this mean for the "energy-soaking model" of *Step 11.a*)?