The Mystery of Light and Wave-Particle Duality (By: Matthew Foss**)**

In Brief:

We will see the mystery of light unfold as it was studied by philosophers and scientists throughout the centuries. At one point it was believed to be a ray of particles. Later it was better described as a wave. Ultimately, our most recent, best understanding is referred to as "wave-particle duality." This lesson will connect with the word on fire video about mystery.

Lesson Scope:

This lesson unit is designed for a high school physics class. It will take at least three class days to complete. The lesson could be modified for use in a chemistry or physical science class. Before starting the lesson, students will take the pre-assessment. In the first part of the lesson, students will briefly learn some of the history of why scientists thought light was a beam of particles and do some of those classic geometric optics experiments. Then students will see why scientists began to think that light was a wave and do some experiments reinforcing this idea. Finally, students will read Einstein's famous paper about the photoelectric effect, which proposes that light can only be explained as both a wave and a particle. They will also conduct photoelectric effect experiments or simulations. As a concluding activity in this sequence of lessons, students will watch the video "Light from Light: Scientific Enigmas and Theological Mysteries" from the Word on Fire series and make connections to philosophical and theological topics, such as the limits of scientific knowledge, based on what they have recently learned throughout this lesson. Finally, they will take the post-assessment.

Lesson Scope:

1. Can scientists develop a consistent theory of light that explains all the observed phenomena?
2. How do scientists appeal to history and authority as they develop their theories?
3. Is it possible to have mystery in science?

Knowledge:

1. Understand the evidence supporting both the particle and wave models of light.
2. Explain how Einstein's interpretation of the photoelectric effect leads to wave-particle duality.
3. Make connections between mystery in science and mystery in religion.

Skills:

1. Evaluate a claim from evidence
2. Test a hypothesis given evidence
3. Synthesize a conclusion taking into account multiple sources of evidence.
4. Analyze a model's ability to explain observable phenomena.

Method:

Part I - Develop the Particle Model of Light

Day 1 - Discussion, Video, Practice, Lecture

1. Have students form small groups to discuss the following questions.
    a. What is light?
    b. How could you describe light to a person who was born blind and never experienced?
    c. As the small groups discuss this, have them record their main points.

2. Have the groups share their descriptions with the larger class. Try to lead them toward making comparisons to other senses and scientific principles. For example, the brightness of light could be compared to a heat source or the loudness of sound. Different colors could be compared to different musical notes.

3. Watch the video of the seventh grader in a dark room.
    a. VIDEO 1 (7 minutes) - "seeing is believing"
    b. After the video, emphasize how convinced the girl was that she could eventually see in the dark.
    c. Teachers should try to help the students realize this point: Once we have established a theory in our minds, it is hard to change our views. This is true even when presented with new, compelling evidence.

4. For centuries, philosophers and early scientists debated whether light has a fixed or infinite speed.
    a. Explain to students that if light has a finite speed, it would obviously be very fast. How could one measure the speed of light?
    b. VIDEO 2: Speed of Light | PBS LearningMedia (4 minutes) - "early measurements of the speed of light". After watching the video, do the activity involving a quick calculation of the speed of light.
    c. After watching the video and completing the practice calculation of the speed of light, teachers should explain the following to the students. Even after Roemer predicted the late arrival of Io's eclipse, scientists did not quickly accept his interpretation. Many of them still believed that light traveled instantly from one place to another, and they had alternate explanations for the delay.

5. Eventually, once Sir Isaac Newton agreed that light had a finite speed, it became widely accepted. Since light has a finite speed, he proposed that it could be a stream of material

particles that acts like a geometric ray. Teachers should explain the following five important points to the students.

a. Newton developed these principles as his “Corpuscular Theory of Light” in his book “Opticks.”

b. The particles of light would be very small, very fast, and perfectly elastic.

c. They are clearly very small particles because we can't really detect them, and if two beams of light overlap, there is little or no interaction between the beams.

d. Rectilinear Propagation seems to demonstrate that light is a fast moving ray of particles. The sharp edges of shadows along with properties from geometry and trigonometry allow us to calculate distances, heights, and angles.

e. Inverse square law for intensity shows that it is a fast moving ray of particles because Intensity is proportional to light quantity divided by distance squared (area).

OUR METHOD (cont'd…)

Day 2 - Activities and Experiments (note: This could take more than one day if you choose to do more than one experiment to demonstrate the particle nature of light.)

1. EXP 1 - Light Intensity
   a. An example of this type of experiment is in the resource section.
   b. This experiment will help students realize that light intensity follows an inverse square law. Not only is this good evidence for the particle model of light, but it will also help students make connections with earlier physics topics like gravitation and electromagnetic force. The inverse square law seems to appear often in nature.

2. EXP 2 - Reflection
   a. An example of this type of experiment is in the resource section.
   b. Reflection of a light ray from a mirrored surface makes sense if light is a ray of particles that experiences an elastic collision with the surface.
   c. If time permits, do more complicated experiments with curved mirrors and/or lenses. Explain the results thinking of light as a ray of particles having elastic collisions with the surfaces.

3. After completing the activities and experiments that you have time to do, discuss the following three points with the students before going to part 2 of the lesson.
   a. Even though Newton's particle model of light explains many phenomena, it does have some problems.
   b. Refraction poses a problem for the particle model of light. It is difficult for his model to explain the bending of a light ray as it moves from one medium into another. He proposed a future experiment where he expected light to travel faster through denser materials, this idea turned out to be wrong!
   c. Diffraction also poses a problem for the particle model of light. The pattern of bright and dark bands seen on a screen after light shines through two narrow openings can not be explained by rectilinear projection.

Part II - Develop the Wave Model of Light

Day 1 - Develop the Wave Model of Light

1. During a brief lecture, teachers should explain the following points.

    a. Light exhibits certain properties that can be better explained if it actually travels through space as a wave rather than a stream of tiny particles.

    b. Diffraction can be fully explained by constructive and destructive interference, which is a property of waves.

    c. Father Francesco Maria Grimaldi, a Jesuit priest, challenged Newton's particle model of light and proposed a wave model of light. He observed that the pattern of bright and dark bands seen on a screen after light shines on a thin rod could not be explained by rectilinear projection.

OUR METHOD (cont'd…)

2. Demonstrate constructive and destructive interference with water waves in a ripple tank (or show a brief video clip).
    a. Teachers should explain: Huygen's wave model of light claims that all points of a wave front may be regarded as new sources of wavelets that expand in every direction. Therefore, light waves would emerge from small openings as spherical waves just like water waves do in analogous situations.
    b. Show Thomas Young's analysis of the double slit experiment, which leads to precise calculation of the location of the dark and bright bands seen in the diffraction pattern.

3. Now, students will work in their lab groups to perform a diffraction experiment.
    a. EXP 3 - Double Slit Diffraction

Day 2- More evidence for the wave model

1. Teachers should explain the following points and have the students do experiment 4 in their lab groups
    a. Refraction (Snell's Law) is fully explained if light is a wave.
    b. Fresnel demonstrated that the speed of light is slower in denser mediums, which also opposes Newton's corpuscular theory of light.
    c. As wave fronts approach a more optically dense material, they slow down causing them to bend toward the normal.
    d. EXP 4 - Refraction
    e. In addition to the experimental evidence for the wave model of light provided by diffraction and refraction, Maxwell provided some theoretical evidence. When Maxwell derived his famous electromagnetic theory equations, he predicted an electromagnetic disturbance that traveled at the exact speed of light previously calculated!

4. So, there is a lot of evidence now for a Wave Model of Light. But, there was a problem. At that time, it was believed that all waves need a medium through which to travel. Teachers can explain the following historical details to the students if time permits:
    a. The idea of a universal Luminiferous Ether through which light propagates was proposed centuries earlier by Aristotle, but it had never been measured or detected.
    b. In 1887, the famous Michelson-Morley experiment yielded results which implied the non-existence of the ether.
    c. How can light be a wave if there is no medium for it to travel through?

OUR METHOD (cont’d…)

PartIII - Wave-Particle Duality

1. We have seen that there are some problems with the particle theory of light.
    a. Diffraction (interference patterns) cannot be explained.
    b. Refraction cannot be properly explained.

2. The wave model seems to be able to explain all observable properties of light, until some interesting observations were made in the early 1900’s.

3. The photoelectric effect (or photoemission) is the process of removing electrons from a surface when light falls on that surface. Teachers should explain the following facts about the photoelectric effect to the class. Then the students should divide into their lab groups to do experiment 5. THis lab can be done using the Phet simulation described in the resource section, because the equipment is quite expensive.
    a. At first, the photoelectric effect causes even more confusion in our understanding of light.
    b. If the wave model is correct, increasing the number of incoming light waves (intensity) that hit the surface should cause an increase in the energy of the electrons that are ejected from the surface. However, when the experiment is performed, increasing the light intensity fails to increase the energy of the ejected electrons.
    c. EXP 5 - The Photoelectric Effect

4. Einstein’s interpretation of data collected from the photoelectric effect experiment "sheds some light" on the situation!
    a. Light seems to travel as if it is a wave. However it interacts with matter like it is a particle.
    b. wave behavior --> Incoming light carries energy equal to the product of Plank's constant and its frequency.
    c. particle behavior --> All the energy in the photon (quanta of light) is delivered to a single electron.
    d. Einstein says it this way. "The simplest conception is that a light quantum (later called a photon) transfers its entire energy to a single electron."

5. Conclusions and Connections
    a. Philosophers and scientists have discussed the nature of light for centuries.
        i. They all had good reasons for their models.
        ii. There were some observations that could not be fully explained by the current theory at the time.

iii. They had to use qualitative (analogies, metaphors, imagination, and speculation) descriptions as well as quantitative measurements (observations, equations, calculations) as they developed their theories.

b. Einstein's explanation of the photoelectric effect is our current best model for light having a mysterious wave-particle duality nature.
   i. Even though it seems impossible for light to be both a wave and a particle at the same time, scientists generally accept this theory as the best we currently have.
   ii. There is mystery in science!

c. Connections to theology
   i. We seem to have an innate desire to search for truth about and understanding of nature.
   ii. History and authority help guide our thinking.