The Wave-Particle Duality of Light

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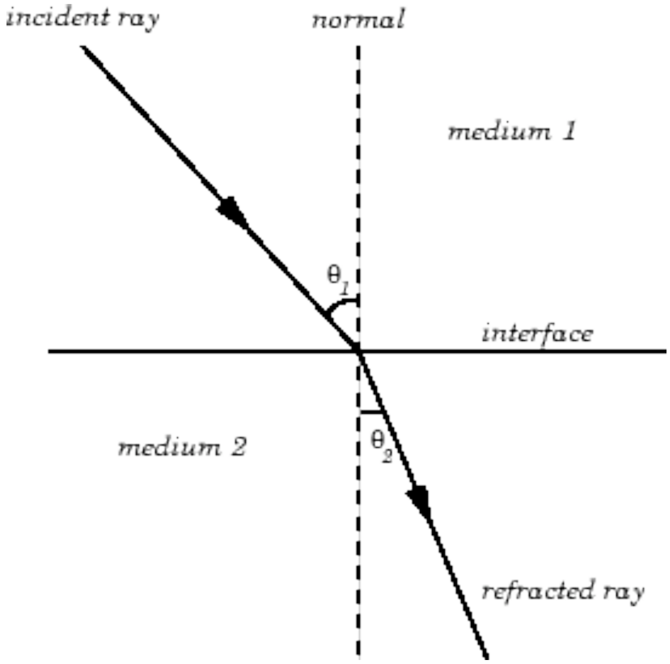
Honors Project, University Physics II, Lab Section: H1

April 25, 2011

Light is an incredible matter. It orchestrates many an extraordinary sky scene, it makes the sense of sight usable, and it is a powerful, and renewable, energy source. Because it initiates photosynthesis, it is absolutely essential for the propagation of life in its present forms. It is, however, difficult to completely and correctly define, as are so many fundamental concepts of the physical world (e.g. gravity or energy). It has properties like those of a particle, as well as properties comparable to those of a wave. Over the past century especially, theories on the nature of light have been embraced, later rejected, and gradually transformed into the currently accepted concept: the wave-particle duality of light. Considering that neither the particle theory nor the wave theory can fully describe the behavior of light, the only reasonable conclusion to approach is that light is, astoundingly, both particles and waves. This fact is made apparent through a close look at the two theories separately coupled with the evidence acquired by means of various groundbreaking experiments.

Isaac Newton introduced the particle theory of light a few hundred years ago and it remained the only recognized theory regarding the composition of light for some time. Newton believed light rays to be “very small Bodies emitted from shining Substances” (Baierlein 1992, 34). It is a logical conjecture, especially for him, because the laws of motion that he developed would apply to small, material particles, while some other unknown constituent would be quite unpredictable. Furthermore, thinking of light as a practically infinite number of tiny solid particles does explain some of its easily observable properties. An example of one such property is the manner in which light reflects off a surface. Light bounces off of a smooth surface in the same way that an elastic, frictionless ball does, in that the angle of incidence is equal to the angle of reflection (Schnatterly 2004, 1). Refraction, or how a light ray bends as it passes through an interface (Stewart 2011, 430), is another characteristic of light that can be explained by the particle model. Steve Schnatterly, while a physics professor at the University of Virginia, explained refraction of light in the following way. In accordance with Newton's first law, the atom-like particles of light should continue to move consistently in a straight line unless a net force is acting on them. Newton supposed that light particles in a material like water or glass feel some sort of force from the particles of the medium, but that within the medium where a light particle is surrounded evenly on all sides by particles of the material, the forces cancel each other out and the motion of the particle is not altered. Near an interface, however, a light particle is not uniformly surrounded by particles of a certain material, so the particle experiences a net force (Schnatterly 2004, 2). It is this net force on individual particles of light that causes a light ray to bend at an interface.

Refraction of light:



(Gardner)

Although Newton's particle theory effectively explains reflection and refraction, there are aspects of reality with which the particle model is not intuitively congruent. Physicist Ralph Baierlein points out that typical objects follow curved paths when thrown or otherwise put into motion, not straight ones, as well as the phenomenon of color (Baierlein 1992, 35, 40). Regular objects follow curved paths because of gravity, of course, and if light is only a bunch of classical particles with some mass, its motion ought to be influenced by gravity as well. In the same way that a bullet shot parallel to the Earth's surface will eventually hit the ground (if it does not hit something else first), light should steadily curve toward the Earth. An incontrovertible behavior of light, though, is that it travels in straight lines from its source, as may be observed through the use of any laser. Newton explained the straight-line motion with the idea that light particles travel so fast that any curvature that occurs is imperceptible (Baierlein 1992, 35). He explained color by suggesting that light particles have different masses: red light is made up of larger, more massive particles than those that make up violet light, so it is deflected less (Baierlein 1992, 40). Despite all of Newton's creative propositions, his theory of light was eventually proved incorrect by an experiment performed by Léon Foucault that produced results (light moves slower in water than in air) he could not explain (Schnatterly 2004, 6). The scientific community shifted its focus quickly from the particle theory to a competing idea: the wave theory of light.

Waves, like particles, are capable of both reflecting and refracting in interactions with various materials; thus, light being made up of waves could potentially account for its behavior. Of the many types of waves, e.g. sound waves, torsional waves, radio waves, etc., water waves are the most useful for simple qualitative comparison to light. For example, water waves that hit some barrier in their path bounce off in the same way that light would, so that the angle of reflection equals the angle of incidence (Baierlein 1992, 68). Water waves also demonstrate the property of refraction. When they pass through a non-uniform medium, the speed and the direction of motion of the waves change (Baierlein 1992, 70). The figure below represents the movement of waves from deep water to more shallow water quantitatively, so that the change of angle in the direction of motion is clearly similar to that seen in light.

Refraction of water waves:

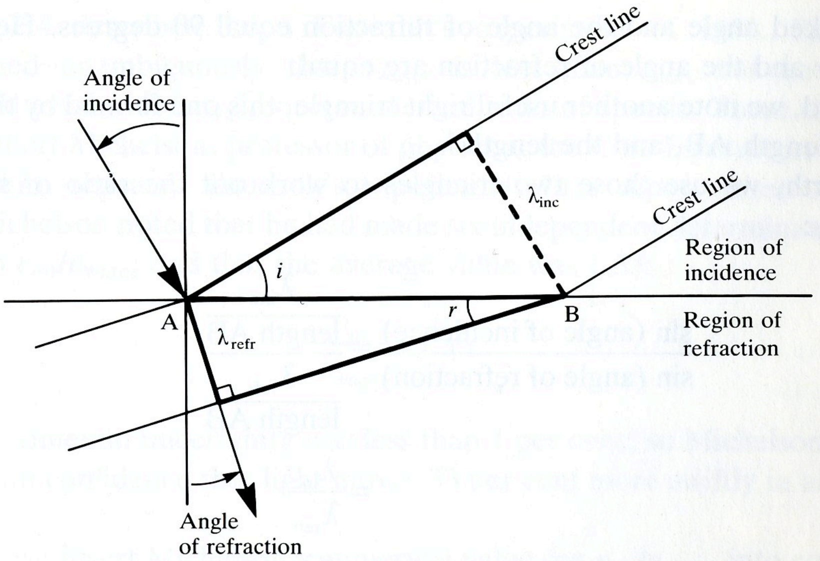


Figure 3.14 The quantitative analysis of refraction. Two adjacent crests appear in the regions of incidence and refraction. The heavier lines outline the two essential triangles.

(Baierlein 1992, 71)

Unlike particles, waves can experience diffraction and also superposition, which allows them to create interference patterns. An important piece of evidence for the accuracy of the wave theory is the Poisson Bright Spot. Siméon Poisson, a mathematician, proposed that if light is actually made of waves, shining a light at a small round disk should cause the light to diffract so that a bright spot is created in the center of the disk's shade (Schäfer 2011, 12). The Spot has been found many times since Poisson suggested its existence, which completely destroys any remaining possibility of the particle theory being entirely true, while reinforcing the rightness of the wave theory. Superposition occurs when two waves interact: they simply add together to form a wave that has a different amplitude than either of the original waves, instead of scattering (Schnatterly 2004, 10). Interference patterns are generated by waves coming from different sources that undergo interactions that are either constructive (resulting wave has a larger amplitude than either of the originals) or destructive (resulting wave has a smaller amplitude than either of the originals). Thomas Young first observed the interference of light by shining a light through two narrow slits that then acted as two sources of "in phase" light (Schnatterly 2004, 16). The following figure shows the pattern that appears:

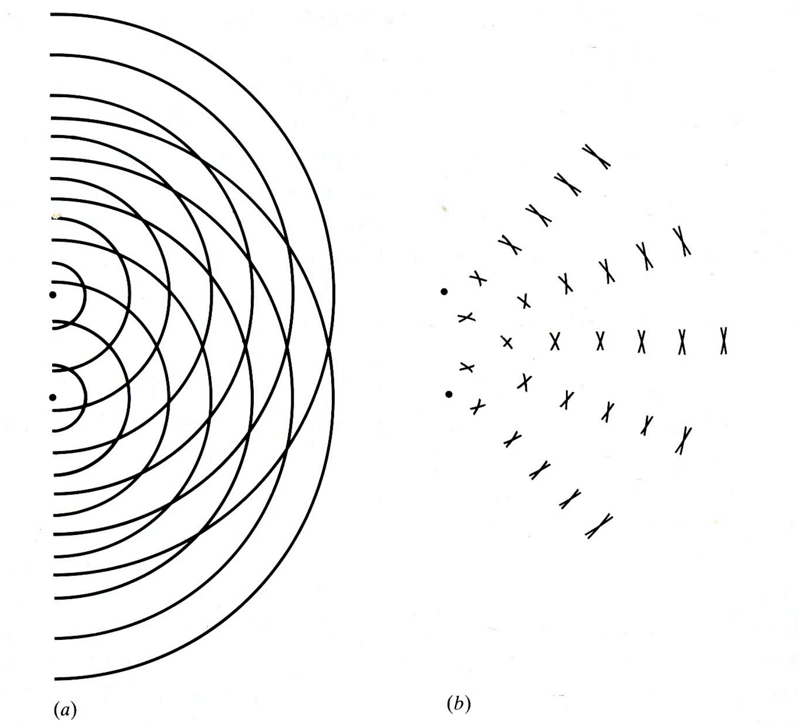


Figure 4.1 Periodic waves from two synchronized sources. The waves are shown at one instant of time, after seven crests have been sent forth. (*a*) The sequences of crest lines, one sequence from each source. (*b*) The locations where a crest line from one source overlaps a crest line from the other and produces constructive interference.

(Baierlein 1992, 82)

Part (b) of the figure above represents the places that would look brightest. Each X marks a place of constructive interference, which denotes greater amplitude. The larger the amplitude is, the greater the intensity or brightness of the light appears. When the interacting waves reach some barrier, the lined up Xs form bright stripes, with dark stripes in between because of destructive interference. The concept of superposition more suitably describes light than the colliding and scattering predicted by the particle theory. Light beams are not witnessed bouncing off of each other. They seem to pass through each other with zero collisions and add together when overlapped. The diffraction, superposition, refraction, and reflection observed in wave interactions can be used to make accurate predictions about the behavior of light. The wave theory is, consequently, a correct description of light, although not necessarily a complete one.

As scientists continued their experiments with light, three particular concepts were developed that do indicate that the wave theory does not fully explicate light: the peculiar nature of black body radiation, the photoelectric effect, and the Compton effect. Analysis of black body radiation ultimately produced bell-shaped curves that classical physics, which assumed that the energy of light was proportional to the time average square of amplitude, could not explain (Schäfer 2011, 3,5). In an attempt to solve this problem, Max Planck found that he could recreate the observed bell-shaped curves with the equation $E = hv$ where E is the energy of light, h is a constant, and v is the frequency of the light. In a beam of monochromatic light with frequency v, only integer multiples of energy hv can be exchanged (Schäfer 2011, 8). Dr. Lothar Schäfer clarifies the subject by comparing a light beam to a stream of coins. If the stream is made up of dimes, one could pull 10 cents, or 40 cents, or 90 cents out of the stream, but never 8 cents or 21 cents or 97 cents (Schäfer 2011, 8). The need for some component to exist in light that could be analogous to a coin in a stream of coins offers a basis for the notion of the photon, a *particle* of light.

Albert Einstein wrote in his paper on the emission and transformation of light that “the energy of a light ray spreading out from a point source is not continuously distributed over an increasing space but consists of a finite number of energy quanta which are localized at points in space, which move without dividing, and which can only be produced and absorbed as complete units” (Milonni 1984, 28). The paper does also articulate the correctness of the wave theory, but it is most famous for Einstein’s prediction of the photoelectric effect (Milonni 1984, 28). The photoelectric effect is the name given to the phenomenon of light being capable of ejecting electrons from a metal (Baierlein 1992, 145). There is a threshold energy required for the process to take place: an electron acquires the energy it needs to be able to escape the attractive force exerted on it by protons in a piece of metal by absorbing light of an appropriate frequency. The amount of energy absorbed by an electron when it absorbs light is always equal to some integer multiple of Planck's constant h times the frequency of the light (Baierlein 1992, 146). If each unit is assigned a quantity of energy hv, Einstein's theory regarding localized "energy quanta", or photons, has experimental support.

The Compton effect was discovered through an experiment conducted by A.H. Compton that involved shooting a beam of x-rays at a block of graphite that split the beam into two: one beam with the same wavelength as the original, and one beam with a longer wavelength than the original (Schäfer 2011, 13). Baierlein explains the interaction in terms of billiard balls, one rolling (analogous to the beam of x-rays) and one initially at rest (like the electrons in the graphite). When the rolling ball hits the stationary ball, both balls continue on with some final velocity. When the x-ray strikes the electron, it imparts energy and causes the electron to recoil, which, like the billiard balls, is a situation to which the law of conservation of energy may be applied (Baierlein 1992, 151). Because the initial velocity of the electron in the graphite is very nearly zero, the x-ray beam must be composed of something(s) that can have mass for the equation to make sense. The fact that the beam must be able to have momentum serves as further confirmation of the actuality of photons, considering that waves do not have mass and ergo cannot have momentum.

Since conclusive evidence is provided for the existence of particles of light as well as for the truth of the wave theory, light is a legitimate conundrum. Dr. Lothar Schäfer summarizes the dilemma well: “It is obvious that the properties of waves and particles are incompatible. Waves are delocalized, can interfere, superpose, interpenetrate, diffract, and some types can propagate in empty space. Particles are localized, inevitably massy, and subject to gravity and inertia… [one] would not expect a single entity to have properties of both particles and waves” (Schäfer 1997, 155). Double-slit experiments do, however, empirically verify that light does have properties of both. If dim enough light is directed through a pair of slits and onto some photoelectric material, an electronic circuitry can easily track the development of the interference pattern as electrons are ejected by the incoming light (Baierlein 1992, 162). The first image presented below was taken after 10 seconds. The second one was taken after 10 minutes.

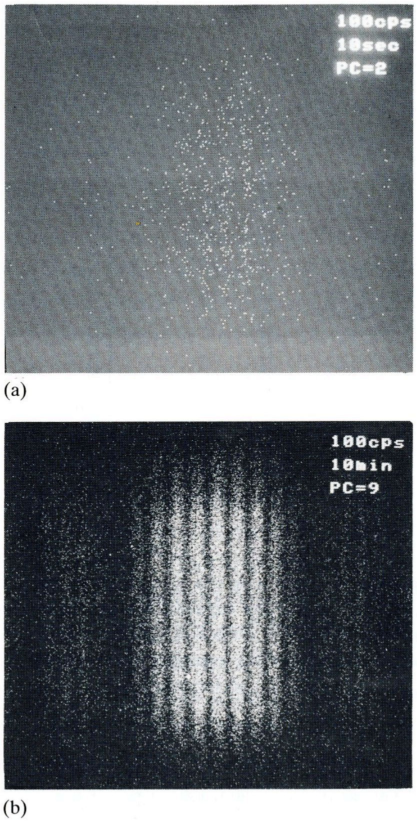


Figure 7.2 The appearance of individual photons in an interference pattern. (*a*) After 10 seconds have elapsed and 1000 photons have been registered. (*b*) After 10 minutes and 60 000 photons. The apparatus was developed by four Japanese physicists, T. Tsuchiya, E. Inuzuka, T. Kurono, and M. Hosoda; they reported their work in a paper entitled “Photon-counting imaging and its application,” published in *Advances in Electronics and Electron Physics*, volume 64A, pages 21–31 (1985).

(Baierlein 1992, 164)

These images are quite remarkable because each tiny bright spot in the first image (a) represents the arrival of an individual photon, and where each one lands is limited undeniably by the wave behavior, that is, the compulsory formation of an interference pattern, as shown in image (b). If the experiment is repeated, the first 1000 photons are registered in different locations, which leads to the conclusion that where an individual photon appears is totally random, "*except* that it never appears where is should not (according to the electromagnetic wave theory)" (Baierlein 1992, 163). Ordinary particles, like bullets, shot through slits at some barrier do not form an interference pattern; instead, they just form two piles in front of each slit that eventually merge into one big pile (Schäfer 2011, 16). The double-slit experiment illustrates plainly that light is truly a fusion of the characteristics of waves and particles, because an interference pattern *is* formed and that pattern is formed by many, many distinct points of light. Baierlein condenses the somewhat intimidating concept into two helpful sentences: "Light is something with the *potentialities* for acting like a wave or a particle, two complementary aspects that are realized under different physical conditions. This complementarity is called the *wave-particle duality*" (Baierlein 1992, 170).

The repercussions of the reality of such an irrational idea are not negligible. Because classical (Newtonian) physics cannot explain the phenomena associated with wave-particle duality, a new branch of science emerged to breach the gap: Quantum Mechanics. Quantum Mechanics describes the behavior of microscopic particles in mathematical terms (Ismael). It is well understood with regard to the actual mechanics of the system, but what sort of world it actually describes – what the world is actually like according to quantum mechanics – is ambiguous (Ismael). The complicatedness ensues because wave-particle duality can describe more than just photons. Elementary particles, like electrons and neutrons, also possess the dual nature (Schäfer 1997, 157). The implication that the physical world is made up of partly material and partly immaterial little pieces is bewildering, but also fascinating.

Even though light is an incredibly common commodity, there is so much more to it than a human eye can see. Separately, both the particle theory of light and the wave theory of light fail to suitably characterize it. Within it, two incongruous features are inexplicably intertwined into one seemingly uniform substance. As exemplified by the Poisson Bright Spot and interference patterns, a light ray must definitely propagate in the form of a wave. As demonstrated by blackbody radiation, the photoelectric effect, and the Compton effect, there must certainly be small packets of energy present in a light ray. Also taking into account the results of the double-slit experiment with very dim light, there can be no doubt that light is of a composite nature, a mysterious nature referred to as wave-particle duality. The existence of such a duality brings the principles of classical physics into question and demands that the world be viewed through Quantum Eyes. Scientists the world over are poking and prodding and adjusting the current perception of reality, all because of the curious behavior of light.

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