2 Nature of Light from the Perspective of a Biologist

What Is a Photon?

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CONTENTS

> The light which makes the plants grow and which gives us warmth has the double characteristics of waves and particles, and is found to exist ultimately of photons. Having carried the analysis of the universe as far as we are able, there thus remains the proton, the electron, and the photon—these three. And, one is tempted to add, the greatest of these is the photon, for it is the life of the atom.
>
> **Arthur Compton (1929)**

2.1 INTRODUCTION

Isaac Newton (1730) asked, "Are not gross Bodies and Light convertible into one another, and may not Bodies receive much of their Activity from the Particles of Light which enter their Composition?" Photosynthesis is the process by which plants and other autotrophic organisms transform the rapidly flowing radiant energy of sunlight into stable and stored chemical energy (Herschel 1833; Mayer 1845; Boltzmann 1886; Franck and Wood 1936; Franck and Herzfeld 1941; Oppenheimer 1941; Arnold and Oppenheimer 1950; Calvin 1959; Arnon 1961; Clayton 1971; Kamen 1985; Laible et al. 1994; Campbell and Norman 1998; Jagendorf 1998; Fuller 1999; Govindjee 2000; Feher 2002; Monteith and Unsworth 2008; Nobel 2009; Wayne 2009b). Photosynthesis, the basic process that feeds the world, begins when the pigments in the antenna complex capture the sunlight and transfer the energy to the pair of chlorophyll molecules that make up the reaction center of a photosystem. The chlorophyll molecules in the reaction center undergo a photochemical charge separation that initiates a sequence of oxidation–reduction reactions that generate an electrochemical potential gradient across the photosynthetic membrane. These electrochemical events facilitate the fixation of carbon dioxide and the evolution of oxygen. These life-sustaining energy conversion processes are initiated by the absorption of a particle of light now known as a photon; but what is a photon?

2.2 QUANTUM MECHANICAL PHOTON AND THE WAVE–PARTICLE DUALITY

Albert Einstein (1905a) described the quantum of light (*Lichtquanten*) like so:

> it seems to me that the observations regarding 'black-body radiation,' photoluminescence, production of cathode rays by ultraviolet light, and other groups of phenomena associated with the production or conversion of light can be understood better if one assumes that the energy of light is discontinuously distributed in space. According to this assumption to be contemplated here, when a light ray is spreading from a point, the energy is not distributed continuously over ever-increasing spaces, but consists of a finite number of energy quanta that are localized in points in space, move without dividing, and can be absorbed or generated only as a whole.

Radiant energy quanta are currently known as photons (from φώτο, the Greek word for light), a name coined independently and with a myriad of meanings by such polymaths as Leonard T. Troland (1916, 1917), John Joly (1921), René Wurmser (1925a,b), Frithiof Wolfers (1926), Gilbert Lewis (1926a,b), and others (Kidd et al. 1989; Kragh 2014).

On the centenary of the publication of Einstein's paper entitled On a Heuristic Point of View Concerning the Production and Transformation of Light, John Rigden (2005) wrote,

> What makes a physics paper revolutionary? Perhaps the most important requirement is that it contains a 'big idea'. Next, the big idea must contradict the accepted wisdom of its time. Third, physicists capable of judging the intrinsic merit of the big idea typically reject it until they are forced to accept it. Finally, the big idea must survive and eventually become part of the woodwork of physics… Einstein's…paper…meets these criteria.

Einstein's mathematical point-like photon differed from Newton's light particle in that the former lacked extension, while the latter had both bigness and sidedness. Many of Einstein's contemporaries, including Max Planck (1920), Niels Bohr (1922), Hendrik Lorentz (1924), and Robert Millikan (1924) did not accept Einstein's model of a mathematical point-like photon since it could not explain the interference of nearby light beams (Einstein 1909c; Stuewer 1989, 2006; Miller 1994; Campos 2004; Rigden 2005). In fact, Einstein "outplancked Planck in not only accepting quantization, but in conceiving of light quanta as actual small packets or particles of energy transferable to single electrons in toto" (Davisson 1937). Einstein's light quantum lacked the spatial extension given to the wavelength of light that is necessary to explain interference and diffraction (Young 1807) that can be observed in soap bubbles, peacock feathers, and the beautiful iridescent blue colors found in a variety of plants, including the leaves of the spike moss, *Selaginella willdenowii*, the leaves of the fern, *Danaea nodosa*, the fruits of *Elaeocarpus angustifolius*, and the petals of the "Queen of the Night" tulip (Lee 2007; Vignolini et al. 2013).

An intuitive description and explanation of interference depends on the wave-like characteristics of light. Classically, the flux of energy or intensity of light depends on the instantaneous amplitude (A) of a monochromatic plane light wave with wavelength λ and frequency ν. The sinusoidally varying amplitude of a light wave is given by

$$A = A_o \sin\left(2\pi\left(\frac{z}{\lambda} \pm \nu t\right)\right) \tag{2.1}$$

where A_o is the maximum amplitude of the wave and may represent the electric field or the magnetic field. The speed $\left(c = \frac{z}{t}\right)$ of the wave is equal to the product of λ and ν. The negative sign inside the argument represents a sinusoidal plane wave moving along the z-axis to the right, and a positive sign represents a sinusoidal plane wave moving along the z-axis to the left. The flux of energy or intensity (I, in W/m^2) of the light wave is proportional to the square of the time average of the amplitude of the electric field (in V/m) and not related to the wavelength or frequency. The intensity is given by

$$I = c\varepsilon_o A^2 = \frac{c\varepsilon_o}{2} A_o^2 \tag{2.2}$$

where $\sin^2 2\pi\left(\frac{z}{\lambda} \pm \nu t\right) = \frac{1}{2}$. Interference effects result when light waves from two sources meet in a given space at the same time. The intensity of the interfering waves depends on the square of the sum of the amplitudes of two (or more) waves and *not* on the sum of the squares:

$$\begin{aligned} I &= c\varepsilon_o(A_1 + A_2 + \ldots + A_n)^2 \\ &\neq c\varepsilon_o(A_1)^2 + c\varepsilon_o(A_2)^2 + \ldots + c\varepsilon_o\left\langle A_n\right\rangle^2 \end{aligned} \tag{2.3}$$

Consequently, waves can both destructively and constructively interfere.

Interestingly, a one-dimensional point-like particle of polychromatic white light can be mathematically modelled by summing an infinite number of plane waves with an infinite number of wavelengths. A larger polychromatic particle of light known as a wave packet can be modelled by summing a group of plane waves with slightly different wavelengths (de Broglie 1924; Bohr 1928; Darwin 1931). Such a particle-like wave packet can be created experimentally with a pinhole and a rapid shutter (Bohm 1979).

Newton's particulate theory of light could not explain the colors of soap bubbles and peacock feathers observed by himself and by Robert Hooke (1665) and the diffraction of light described and named by Francesco Maria Grimaldi (1665). However, these phenomena could be explained at the turn of the nineteenth century by Thomas Young (1804, 1807; Anon 1804) in terms of the interference of light waves. By the end of the nineteenth century, as a result of the successes of James Clerk Maxwell's (1865) electromagnetic wave theory and Heinrich Hertz's (1893) demonstration that electromagnetic waves obey the laws of optics, the wave theory of light (Huygens 1690), which itself had been marginalized by the particulate theory of light, was resurrected and improved, and its proponents relegated Newton's particulate theory of light to the sidelines (Stokes 1884). At the *fin de siècle*, Albert Michelson (1903) triumphantly wrote, "The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote." However, Lord Kelvin (1904) recognized that there were *nineteenth century clouds* over the wave theory of light created in part by the results of the Michelson–Morley experiment (Michelson and Morley 1887). Some of these clouds would blow over following the introduction of the quantum mechanical, mathematical point-like photon, which could explain the photoelectric effect (Einstein 1905a), while others would remain since it was not possible to describe and explain interference in terms of the mathematical point-like quantum mechanical photon.

Experiments performed in the later part of the nineteenth century by Hertz and Philipp Lenard led to the idea that there was more to the description of the energy of light than just the intensity given by the wave theory. While doing research to experimentally verify Maxwell's electromagnetic wave theory that predicted the propagation of electromagnetic waves through space (Yang 2014), Hertz

(1887) discovered serendipitously that the ultraviolet light produced by the spark gap powered by an oscillating high-voltage coil that he used to transmit electromagnetic waves enhanced the ability of the receiver, which was a copper wire loop with a gap, to produce a spark (Klassen 2011). The presence of a spark in the gap of the receiver that was unconnected to the transmitter was proof that the electromagnetic waves had been transmitted from the transmitter to the receiver through space. Although Hertz hoped that he would be able to see the spark produced in the receiver better when he put it in the dark, he found that when he covered the receiver, the spark it produced was much weaker. The ultraviolet light from the transmitter sparks enhanced spark production in the receiver. This ultraviolet light-induced production of an electric spark became known as the photoelectric effect. The photoelectric effect is a physical analogue of the charge separation that takes place in the photosynthetic reaction center.

Lenard (1900, 1902), who had been an assistant of Hertz, placed the spark gap in a vacuum tube that allowed him to produce a photocurrent instead of a spark in response to ultraviolet irradiation. By moving the actinic spark light closer to the metal, Lenard showed that the magnitude of the photocurrent produced across the spark gap in the vacuum tube, which was a measure of the number of ejected photoelectrons, was a function of the ultraviolet light intensity that fell upon the metal cathode.

Lenard found that he could accelerate or retard the photoelectrons ejected from the metal by applying electrical energy in forward bias and reverse bias mode, respectively, between the negatively charged cathode from which the electrons were emitted and the positively charged anode to which the electrons traveled. He placed an electric field in the reverse bias mode so that it diminished the kinetic energy of the emitted photoelectrons. When the electric field was small, the photoelectrons had high kinetic energy, and when the electric field was large, the photoelectrons had reduced kinetic energy. At one electric field strength, the photoelectrons had zero kinetic energy. Lenard realized that the photoelectrons could only be ejected from the metal atoms if their kinetic energy exceeded the binding energy. Lenard equated the binding energy with the electrical energy that would produce a photoelectron with zero kinetic energy. Lenard found that he could not cause the photoelectrons to be ejected at the threshold electrical potential nor could he cause the ejected photoelectrons to gain additional kinetic energy by increasing the intensity of the actinic light provided by the arc lamp by either moving it closer or increasing the current that flowed through it. However, he did find that the kinetic energy of the ejected photoelectrons did depend on the type of light he used. Lenard (1902) suggested that the spectral composition (i.e., frequency) of the light determined the characteristics of the photoelectrons that were ejected from the atom by ultraviolet light (Thomson 1908; Wheaton 1978, 1983)—a prediction that was confirmed by Millikan (1950) in 1912.

Looking at Lenard's (1902) experimental results, Einstein (1905a) realized that the photoelectric effect could be understood better if the energy of light was discontinuously distributed in space. Einstein wrote,

> According to the conception that the exciting light consists of energy quanta of energy $\left(\frac{R}{N}\right)\beta\nu$, the production of cathode rays by light can be conceived in the following way. The body's surface layer is penetrated by energy quanta whose energy is converted at least partially to kinetic energy of electrons. The simplest possibility is that a light quantum transfers its entire energy to a single electron; we will assume that this can occur. However, we will not exclude the possibility that the electrons absorb only a part of the energy of the light quanta. An electron provided with kinetic energy in the interior of the body will have lost a part of its kinetic energy by the time it reaches the surface. In addition, it will have to be assumed that in leaving the body, each electron has to do some work P (characteristic of the body).

Einstein presented a heuristic equation to describe the photoelectric effect like so:

$$KE = \frac{R}{N}\beta\nu - P \tag{2.4}$$

where KE is the kinetic energy of the ejected photoelectron, P is the amount of work that must be done by the quantum of light just to overcome the attractive force between the electron and the nucleus; $\frac{R}{N}$ is the ratio of the universal gas constant to Avogadro's number and is equal to Boltzmann's constant; and β is the ratio of Planck's constant to Boltzmann's constant. Consequently, $\frac{R}{N}\beta\nu = h\nu$. By changing P to W to stand for the work function, the modern form of Einstein's equation for the kinetic energy $\left(KE = \frac{1}{2}mv^2\right)$ of the photoelectron becomes

$$KE = h\nu - W \tag{2.5}$$

Einstein (1905a) wrote that

> As far as I can see, our conception does not conflict with the properties of the photoelectric effect observed by Mr. Lenard. If each energy quantum of the exciting light transmits its energy to electrons independent of all others, then the velocity distribution of the electrons, i.e., the quality of the cathode rays produced, will be independent of the intensity of the exciting light; on the other hand, under otherwise identical circumstances, the number of electrons leaving the body will be proportional to the intensity of the exciting light.

"After ten years of testing and changing and learning and sometimes blundering," Millikan (1916, 1924) provided the experimental proof using the photoelectric effect that quantitatively confirmed the validity of Einstein's equation describing "the bold, not to say the reckless, hypothesis of an electro-magnetic light corpuscle of energy $h\nu$, which energy was transferred upon absorption to an electron." The slope of the line that related the kinetic energy of the photoelectrons ejected from sodium and lithium metal to the frequency of the incident ultraviolet and visible light was equal to Planck's constant, and the product of the *x-intercept* and Planck's constant was equal to the work function (Millikan 1914, 1916, 1924, 1935). William Duane and Franklin Hunt (1915) designed an experiment that was the reverse of the photoelectric effect and showed that, consistent with Equation 2.5, the energy of the x-rays emitted from a metal in a vacuum tube was proportional to the kinetic energy of the electrons that were used to bombard the metal. Their results supported Einstein's hypothesis concerning the proportionality between the energy of a photon and frequency of light.

Charles D. Ellis (1921, 1926; Ellis and Skinner 1924a,b) extended Millikan's experiments on the photoelectric effect to the x-ray range and showed that the slope of the graph that related the kinetic energy of photoelectrons to the frequency of incident x-rays was the same for different metals. This supported the idea that Planck's constant was a property of all photons.

These experimental confirmations of Einstein's heuristic proposal that the energy of a photon was related to its wavelength or frequency, but not its amplitude, were quite a blow to the wave theory of light (Einstein 1931), although Millikan (1924) was not convinced as he expressed in his Nobel Lecture,

> …the general validity of Einstein's equation is, I think, now universally conceded, and to that extent the reality of Einstein's light-quanta may be considered as experimentally established. But the conception of localized [point-like] light-quanta out of which Einstein got his equation must still be regarded as far from being established…It may be said then without hesitation that it is not merely the Einstein equation which is having extraordinary success at the moment, but the Einstein conception as well. But until it can account for the facts on interference and the other effects which have seemed thus far to be irreconcilable with it, we must withhold our full assent. Possible the recent steps taken by Duane, Compton, Epstein and Ehrenfest may ultimately bear fruit in bringing even interference under the control of localized light-quanta. But as yet the path is dark.

Additional support for Einstein's point-like quantum of light came from experiments done by Arthur Compton using x-rays. Compton (1923) scattered x-rays from the electrons of graphite (carbon) and measured the wavelength of the scattered x-rays with an x-ray diffraction grating spectrometer. He discovered that the wavelength of the scattered x-rays was longer than the wavelength of the incident x-rays. Compton realized that if x-rays were considered to be particles with energy and linear momentum,* and if both energy and linear momentum were conserved in a collision between a photon and an electron, as they are in collisions between massive particles, then the wavelength of the x-rays scattered from a recoiling electron would be greater than the wavelength of the incident x-rays. Compton found that the red shift in the wavelength of the scattered radiation was also consistent with the Doppler effect since the recoiling electron was actually moving away from the incident and scattered x-ray photons. The interpretation of the Compton effect was a double bonus for Einstein since Compton also found that the recoil of the electron caused by the high energy photons could only be explained by taking into consideration Einstein's (1905b) special theory of relativity.

Chandrasekhara V. Raman (1930) provided further support for the particulate nature of light by performing experiments that were an optical analogue of the Compton effect. Raman showed that long wavelength light described by ultraviolet, visible, and infrared wavelengths was scattered by the vibrating electrons of molecules as if the light had a particulate nature. Depending on the direction of movement of the electrons, the incident light could lose or gain energy and linear momentum resulting in a lengthening or shortening of the wavelength (Wayne 2014a). Likewise, x-rays can gain energy and linear momentum from interacting with electrons moving toward them, which results in a shortening of their wavelength in a process known as the inverse Compton or the Sunyaev–Zel'dovich effect (Rybicki and Lightman 1979; Shu 1982).

For nearly a century, the widely accepted quantum mechanical model has described the photon as a point-like elementary particle or wave packet characterized by the following four quantities: speed, energy, linear momentum, and angular momentum (Jeans 1914, 1924; Jordan 1928; Darwin 1931; Heitler 1944; Weinberg 1975; Feynman 1979; Loudon 1983; Zeilinger et al. 2005; Bialynicki-Birula 2006). The speed (c) of a photon in free space is defined as a constant equal to 2.99792458×10^8 m/s (Jaffe 1960; Livingston 1973). The speed of light is related to two other constants of nature: the electrical permittivity of the vacuum ($\varepsilon_o = 8.854187817 \times 10^{-12}$ F m^{-1}) and the magnetic permeability of the vacuum ($\mu_o = 4\pi \times 10^{-7}$ H m^{-1}) by the following equation:

$$c = \frac{1}{\sqrt{\varepsilon_o \mu_o}} \tag{2.6}$$

The energy (E) of a photon is given by

$$E = \frac{hc}{\lambda} = \hbar ck \tag{2.7}$$

where h is Planck's constant ($6.62606957 \times 10^{-34}$ J s), $\hbar$ or h-bar is the reduced Planck's constant $\left(\hbar = \frac{h}{2\pi} = 1.055 \times 10^{-34}\ \text{J s}\right)$, λ is the wavelength of the photon, and k is the angular wave

* When the mass is constant and invariant, the linear momentum (Leibnitz's dead force or *vis mortua*) is equal to the derivative of the kinetic energy (Leibnitz's living force or *vis viva*) with respect to velocity:

$$\frac{dKE}{dv} = \frac{d\frac{1}{2}mv^2}{dv} = mv.$$

number of the photon $\left(=\frac{2\pi}{\lambda}\right)$. The wavelength of a photon is inversely proportional to its energy:

$$\lambda = \frac{hc}{E} \tag{2.8}$$

The proportionality constant between energy and wavelength is hc (= 1.99 × 10^{-25} J m). The wavelength of the quantum mechanical photon represents only a number and not spatial wave-like properties. Since the frequency (ν) of the quantum mechanical photon is equal to the ratio of its speed to its wavelength as given by the dispersion relation $\left(\nu = \frac{c}{\lambda}\right)$, the energy of a photon in free space that is traveling at a speed c is also given by

$$E = h\nu = \hbar\omega \tag{2.9}$$

where h is the proportionality constant between the energy of a photon and its frequency. The angular frequency ω equals $2\pi\nu$, and the dispersion relation is $c = \frac{\omega}{k} = \frac{2\pi\nu}{2\pi/\lambda} = \nu\lambda$. Energy is a scalar quantity that only has magnitude and is easy to work with algebraically. Linear momentum, on the other hand, is more difficult to work with since it is a vector quantity that has both direction and magnitude. This was especially true in the early years of the fledgling field of quantum theory, and linear momentum had not been included in Einstein's (1905a) original concept of the quantum of light.

The linear momentum (p) of a massive body is equal to the product of the mass (m) of the body and its velocity (v). Johannes Stark (1909) took the unidirectional nature of light propagation into serious consideration and stated that the linear momentum (p) of a photon is parallel to the direction of propagation and is related to its energy (E) in the following manner:

$$p = \frac{E}{c} \tag{2.10}$$

where the speed of light is a constant that relates the linear momentum of a photon to its energy. Consequently,

$$p = \frac{h\nu}{c} = \frac{h}{\lambda} = \hbar k \tag{2.11}$$

The fact that the linear momentum of light is capable of exerting a radiation pressure was already predicted by electromagnetic wave theory (Maxwell 1873; Poynting 1904) and experimentally measured (Lebedew 1901; Nichols and Hull 1903a,b). Moreover, the fact that energy and linear momentum are conserved in collisions between photons and electrons supports the particulate nature of the photon and also suggests that the photon has some kind of mass associated with it. Since the linear momentum of a photon is inversely proportional to its wavelength, photons in the x-ray range (λ = 0.01–10 nm) have very large linear momenta. Since photons propagate at the speed of light ($v = c$), the linear momentum can be considered to be given by

$$p = mv = mc \tag{2.12}$$

And since $p = mc$ and $E = pc$, then

$$E = mcc \tag{2.13}$$

which is more commonly written as the world's most famous equation:

$$E = mc^2 \tag{2.14}$$

This equation states that mass and energy are transformable. It is helpful in understanding many high energy processes. One such process is the transformation of the mass of protons into the lesser mass of helium nuclei with the attendant release of radiant energy that occurs in the core of the sun (Bethe 1967), and that makes photosynthesis on earth possible.

In addition to linear momentum, each photon has angular momentum (L), a three-dimensional vector quantity that is even more difficult to work with than linear momentum and was a latecomer to quantum theory. The angular momentum of each and every photon is given by the following equation:

$$L = \frac{h}{2\pi} = \hbar \tag{2.15}$$

where $\hbar$ is the product of energy and time (Schuster and Nicholson 1924). The angular momentum of a photon was determined by Beth (1936) by measuring the torque exerted on a birefringent crystal by polarized light. Interestingly, the angular momentum, which like linear momentum is also a vector quantity, is unique in terms of conserved quantities in that it is the only conserved property shared by all photons, independent of their frequency and wavelength. The angular momentum* of a photon is related to its total energy (E) by the following relationships:

$$L = \hbar = \frac{h}{2\pi} = \frac{h\nu}{2\pi\nu} = \frac{E}{2\pi\nu} = \frac{E}{\omega} \tag{2.16}$$

* Historically, there has been contention concerning the relation between rotational motion and spin (Tomonaga 2007). According to Landau and Lifshitz (1958), "in quantum mechanics, some 'intrinsic' angular momentum must be ascribed to an elementary particle, regardless of its motion in space. This property of elementary particles is peculiar to quantum theory…, and hence is essentially incapable of a classical interpretation. In particular, it would be wholly meaningless to imagine the 'intrinsic' angular momentum of an elementary particle as being the result of its rotation about 'its own axis', if only because we cannot ascribe any finite dimensions to an elementary particle."

The quantum mechanical photon is characterized by its contradictory and seemingly irreconcilable particle-like properties such as mass and linear momentum and wave-like properties such as wavelength and frequency. Max Born (1963) described particle–wave duality like so:

> The ultimate origin of this difficulty lies in the fact (or philosophical principle) that we are compelled to use the words of common language when we wish to describe a phenomenon, not by logical or mathematical analysis, but by a picture appealing to the imagination. Common language has grown by everyday experience and can never surpass these limits. Classical physics has restricted itself to the use of concepts of this kind; by analysing visible motions it has developed two ways of representing them by elementary processes: moving particles and waves. There is no other way of giving a pictorial description of motions—we have to apply it even in the region of atomic processes, where classical physics breaks down. Every process can be interpreted either in terms of corpuscles or in terms of waves, but on the other hand it is beyond our power to produce proof that it is actually corpuscles or waves with which we are dealing, for we cannot simultaneously determine all the other properties which are distinctive of a corpuscle or of a wave, as the case may be. We can therefore say that the wave and corpuscular descriptions are only to be regarded as complementary ways of viewing one and the same objective process, a process which only in definite limiting cases admits of complete pictorial interpretation. It is just the limited feasibility of measurements that defines the boundaries between our concepts of a particle and a wave. The corpuscular description means at the bottom that we carry out the measurements with the object of getting exact information about momentum and energy relations (e.g. the Compton effect), while experiments which amount to determinations of place and time we can always picture to ourselves in terms of the wave representation….

It seems to me that the longer the wavelength of a photon, the better the wave model describes its interactions with matter, and the shorter the wavelength of the photon, the better a mathematical point describes its interactions with matter. In his Nobel Lecture, Arthur Compton (1927) offered these thoughts:

> An examination of the spectrum of the secondary X-rays shows that the primary beam has been split into two parts… one of the same wavelength and the other of increased wavelength. When different primary wavelengths are used, we find always the same difference in wavelength between these two components; but the relative intensity of the two components changes. For the longer wavelengths the unmodified ray has the greater energy, while for the shorter wavelengths the modified ray is predominant. In fact when hard γ-rays are employed, it is not possible to find any radiation of the original wavelength. Thus in the wavelength of secondary radiation we have a gradually increasing departure from the classical electron theory of scattering as we go from the optical region to the region of X-rays and γ-rays…. According to the classical theory, an electromagnetic wave is scattered when it sets the electrons which it traverses into forced oscillations, and these oscillating electrons reradiate the energy which they receive. In order to account for the change in wavelength of the scattered rays, however, we have had to adopt a wholly different picture of the scattering process…. Here we do not think of the X-rays as waves but as light corpuscles, quanta, or, as we may call them, photons. Moreover, there is nothing here of the forced oscillation pictured on the classical view, but a sort of elastic collision, in which the energy and momentum are conserved…. Thus we see that as a study of the scattering of radiation is extended into the very high frequencies of X-rays, the manner of scattering changes. For the lower frequencies the phenomena could be accounted for in terms of waves. For these higher frequencies we can find no interpretation of the scattering except in terms of the deflection of corpuscles or photons of radiation. Yet it is certain that the two types of radiation, light and X-rays, are essentially the same kind of thing. We are thus confronted with the dilemma of having before us a convincing evidence that radiation consists of waves, and at the same time that it consists of corpuscles…. Thus by a study of X-rays as a branch of optics we have found in X-rays all of the well-known wave characteristics of light, but we have found also that we must consider these rays as moving in directed quanta. It is these changes in the laws of optics when extended to the realm of X-rays that have been in large measure responsible for the recent revision of our ideas regarding the nature of the atom and of radiation.

Neither the quantum mechanical model of a mathematical point-like photon nor the classical model of light as an infinite plane wave is sufficient on their own to explain all the observable interactions of light with matter. William Henry Bragg (1922) described the situation in 1921 like so:

> On Mondays, Wednesdays and Fridays, we use the wave theory; on Tuesdays, Thursdays and Saturdays we think in streams of flying quanta or corpuscles. That is after all a very proper attitude to take. We cannot state the whole truth since we have only partial statements, each covering a portion of the field. When we want to work in any one portion of the field or other, we must take out the right map. Some day we shall piece all the maps together.

In 1938, Einstein and Leopold Infeld asked,

> But what is light really? Is it a wave or a shower of photons? Once before we put a similar question when we asked: is light a wave or a shower of light corpuscles? At that time there was every reason for discarding the corpuscular theory of light and accepting the wave theory, which covered all phenomena. Now, however, the problem is much more complicated. There seems no likelihood for forming a consistent description of the phenomena of light by a choice of only one of the two languages. It seems as though we must use sometimes the one theory and sometimes the other, while at times we may use either. We are faced with a new kind of difficulty. We have two contradictory pictures of reality; separately neither of them fully explains the phenomena of light, but together they do.

In his *own obituary*, Einstein (1949) wrote,

> The double nature of radiation (and of material corpuscles) is a major property of reality, which has been interpreted

> by quantum-mechanics in an ingenious and amazingly successful fashion. This interpretation, which is looked upon as essentially final by almost all contemporary physicists, appears to me as only a temporary way out….

While Einstein saw the Copenhagen interpretation of the wave–particle duality of light as a temporary fix, Niels Bohr (1934, 1958, 1963; see Jammer 1966) saw it as a fundamental aspect of reality when he wrote, "we are compelled to acknowledge... a new trait which is not describable in terms of spatiotemporal pictures… [and we must envision processes] which are incompatible with the properties of mechanical models…and which defy the use of ordinary space–time models." While the irreconcilability of the wave–particle duality and the principle of complementarity has become an *idola tribus* (R. Bacon 1267; F. Bacon 1620) among almost all contemporary physicists, perhaps it is possible to take the best parts of both theories to get a synthetic and realistic model of a photon that can describe both gamma rays and radio waves. Such a theory should be approximated by the quantum mechanical mathematical point-like photon in the gamma ray region and by the wave theory that describes infinite plane waves in the radio wave region of the spectrum.

2.3 BINARY PHOTON

In the quantum mechanical, mathematical point-like model of the photon, there is no indication of how the photon can transfer the electromagnetic force from an emitter to an absorber (Lehnert 2006, 2008). Here I will present a model of a photon that has bigness and sidedness as Newton (1730) would say. The extension beyond that of a mathematical point allows the carrier of the electromagnetic force to possess an electric dipole moment and a magnetic moment. I will derive the finite transversal dimension of the photon from its angular momentum, linear momentum, and energy. I will also describe why I think that the photon is not an elementary particle but is divisible—being composed of two component parts that oscillate and rotate in such a way to generate wave-like behavior. Perhaps such wave-like behavior is what allows a single photon to interfere with itself when subject to an obstruction (Taylor 1909; Tsuchiya et al. 1985). Notable physicists such as William Bragg (1907a,b,c, 1911, 1933; Bragg and Madsen 1908), Louis de Broglie (1924, 1932a,b,c, 1933, 1934a,b,c,d, 1939; de Broglie and Winter 1934), Pascual Jordan (1935, 1936a,b,c, 1937a,b; Jordan and Kronig 1936), and others (Kronig 1935a,b,c, 1936; Scherzer 1935; Born and Nagendra Nath 1936a,b; Fock 1936, 1937; Nagendra Nath 1936; Sokolow 1937; Pryce 1938; Rao 1938; Greenberg and Wightman 1955; Case 1957; Rosen and Singer 1959; Barbour et al. 1963; Ferretti 1964; Perkins 1965, 1972; Ruderfer 1965, 1971; Broido 1967; Bandyopadhyay and Ray Choudhuri 1971; Inoue et al. 1972; Sarkar et al. 1975; Clapp 1980; Dvoeglazov 1998, 1999; Varlamov 2002; Beswick and Rizzo 2008) have proffered, modified, or refuted models of a binary photon* composed of two semiphotons.

Some particles, such as neutral mesons that were once thought to be elementary, have turned out to be composite particles (Dirac 1933; Fermi and Yang 1949). I start with the assumption that the photon may not be an elementary particle, but a binary structure consisting of two semiphotons†—one a particle of matter and the other an antiparticle of antimatter (Wayne 2009a). I have defined matter as having a positive mass and antimatter as having a negative mass (Ginzburg and Wayne 2012; Wayne, 2012c, 2013b). Negative mass is a legitimate (Belletête and Paranjape 2013; Mbarek and Paranjape 2014) although an unwelcomed (Dirac 1930, 1931; Djerassi and Hoffmann 2001) concept in physics. The cosmologist Hermann Bondi (1957) characterized many of its properties. The particle and antiparticle that make up a binary photon are conjugate in that they have equal and opposite mass (M), charge (C), and sense of rotation or parity (P). The sums of two masses or two charges that are equal in magnitude but opposite in sign are zero. Thus, a binary photon in free space is massless and charge-neutral, as is required (Okun 2006; Altschul 2008; Olive et al. 2014). Although the binary photon is neutral as a result of being composed of two conjugate‡ semiphotons, it can form an electric dipole moment and a magnetic moment, which one could argue is a *sine qua non* for a photon to carry the electromagnetic force. Moreover, since the senses of rotation and the signs of the masses are opposite, the angular momenta of the two particles do not cancel each other but add to each other such that the binary photon has angular momentum ($L = \hbar$).

By contrast, the standard model of physics defines the conjugate particles of matter and antimatter as differing in charge (C), sense of rotation or parity (P), and direction in time (T), which gives CPT symmetry (Feynman 1987). According to Richard Feynman (1985), "Every particle in nature has an amplitude to move backwards in time, and therefore has an anti-particle…" Assuming that time is most accurately described as being unidirectional (Wayne 2012a, 2013b), I define the conjugate particles of matter and antimatter as differing in charge (C), sense of rotation or parity (P), and mass (M), which gives CPM symmetry (Wayne 2012c).

In order to travel at the speed of light, according to de Broglie (1930), the photon in free space must be massless, even

* Sing to the tune of Mack the Knife (Pais 1986):

Und Herr Jordan	Mister Jordan
Nimmt Neutrinos	Takes neutrinos
Und daraus baut	And from those he
Er das Licht	Builds the light
Und sie fahren	And in pairs they
Stets in Paaren	Always travel
Ein Neutrino	One neutrino's
Sieht man nicht	Out of sight

† Edwin Salpeter came to Cornell to work on the model of a binary photon with Hans Bethe (personal communication).

‡ From the Latin word *conjugare* meaning yoked together, united, or married and from the mathematical meaning of changing the sign from positive to negative or negative to positive.

though it has energy $\left(E = \frac{hc}{\lambda}\right)$, linear momentum $\left(p = \frac{h}{\lambda}\right)$, and angular momentum ($L = \hbar$) that can be observably transferred to any object with which it interacts. However, given the measured energy ($E = mc^2$) and linear momentum ($p = mc$) of a photon, the observable photon must by necessity also have a measurable mass (Haas 1928; Ruark and Urey 1930; O'Leary 1964; Young 1976) when it interacts with either matter or antimatter. The mass transferred to the object is given by the following equation:

$$m = \pm\frac{h\nu}{c^2} \tag{2.17}$$

where the + sign describes the mass of a photon interacting with matter, and the – sign describes the mass of a photon interacting with antimatter. I assume that measurements made with an equal number of matter and antimatter detectors that would separately give a positive or a negative mass, respectively, when added together would give a vanishing photon mass.

Newton's Second Law was written only for bodies with positive mass, which was reasonable because no other substance besides matter was known. I have generalized Newton's Second Law to include masses that are positive and negative (Wayne 2009a). According to the generalized Second Law of Newton, the ratio* of the inertial force ($\boldsymbol{F}$) to acceleration ($\boldsymbol{a}$) of a body is given by

$$m = \frac{\boldsymbol{F}}{\boldsymbol{a}} \tag{2.18}$$

where mass (m) is a scalar quantity with sign and magnitude, and force and acceleration are vector quantities with magnitude and direction in space. The vector of acceleration is parallel to the force vector for a positive mass, and the two vectors are antiparallel for a negative mass. Specifically, a positive mass will accelerate toward an attractive force, and a negative mass will accelerate away from an attractive force (Figure 2.1). A positive mass will accelerate away from a repulsive force, and a negative mass will accelerate toward a repulsive force.

How do particles of negative and positive mass interact with themselves and with each other? At the onset, if we consider the particles to have mass but not charge, then we can use Newton's Law of Gravitation in a generalized version to describe the causal force and Newton's (1687) Second Law in a generalized version to determine how any two particles, with masses of arbitrary sign, respond to the causal force and accelerate relative to each other (Wayne 2009a).

* The vector division is done with vectors that have direction in one-dimensional vector space where their magnitudes are described by real numbers and their directions are either parallel or antiparallel.

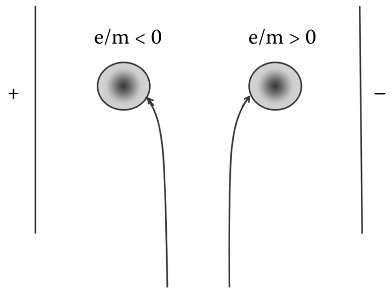

FIGURE 2.1 In an electric field, a particle, such as an electron with a charge-to-mass (e/m) ratio less than zero, accelerates toward an attractive force and bends toward the positive plate. A negative mass electron (= positron), with a charge-to-mass ratio greater than zero, accelerates away from the positive plate.

By equating the causal gravitational force ($\boldsymbol{F}_g$) to the responsive inertial force ($\boldsymbol{F}_i$) we get

$$\frac{G}{r^2} m_1 m_2 \hat{\boldsymbol{r}} = \boldsymbol{F}_g = \boldsymbol{F}_i = m_2 \boldsymbol{g} \tag{2.19}$$

where r is the distance between the two masses, $\hat{\boldsymbol{r}}$ is the unit vector from m_2 to m_1, G is the gravitational constant (6.673003×10^{11} m^3 kg^{-1} s^{-2}), m_1 is the mass of a large body like the earth or the sun, m_2 is the test mass, and $\boldsymbol{g}$ is the acceleration due to gravity of the test mass relative to the large body (Figure 2.2). The test mass accelerates toward the large body when $\boldsymbol{g} > 0$, and the test body accelerates away from the large body when $\boldsymbol{g} < 0$. When $\boldsymbol{F}_g > 0$, there are like masses and the gravitational force is attractive. When $\boldsymbol{F}_g < 0$, there are unlike masses and the gravitational force is repulsive. The relationship between the gravitational force and the acceleration for any combination of masses can be obtained by plugging masses of various signs into the above equation.

For example, when the mass of a large body such as the earth is positive, there will be an attractive force ($\boldsymbol{F}_g > 0$) between it and a positive test mass. Consequently, the positive test mass will accelerate toward the large positive mass ($\boldsymbol{g} > 0$). When the mass of a large body is positive, there will be a

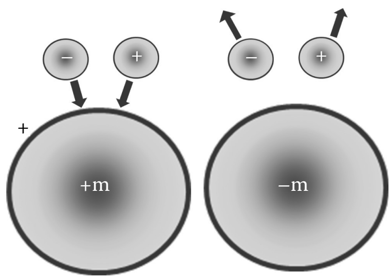

FIGURE 2.2 The direction of acceleration of positive and negative test masses relative to a large body composed of positive or negative mass. Positive and negative test masses accelerate toward a large body composed of positive mass, while positive and negative test masses accelerate away from a large body composed of negative mass.

repulsive force ($F_g < 0$) between it and a negative test mass. Consequently, the negative test mass will accelerate toward the large positive mass ($g > 0$). Recent tests on the effect of gravity on antimatter supports this conjecture (ALPHA Collaboration and A. E. Charman 2013).

When the mass of a large body is negative, there will be a repulsive force ($F_g < 0$) between it and a positive test mass. Consequently, the positive test mass will accelerate away from the large negative mass ($g < 0$). When the mass of a large body is negative, there will be an attractive force ($F_g > 0$) between it and a negative test mass. Consequently, the negative test mass will accelerate away from the large positive mass ($g > 0$).

Now for the interesting part that is relevant for the binary photon. If the magnitudes of the masses of a negative mass particle and a positive mass particle are the same, the positive mass particle will accelerate away from the negative mass particle ($g < 0$), and the negative mass particle will accelerate toward the positive mass particle ($g > 0$). Consequently, the negative mass particle will chase the positive mass particle (Figure 2.3). Since $\frac{G}{r^2}m_1m_2$ is the same for the two semiphotons but the signs of $\hat{r}$ are opposite, the force exerted by each semiphoton on the other is equal and opposite, and the propagating binary photon obeys Newton's Third Law.

I suggest that the gravitational force between the two conjugate semiphotons that make up the binary photon provides the motive force that causes a photon to move. While this is the only dynamic answer I know of to the question "what causes light to move?" it contradicts the widely held assumption that the gravitational force, which is the weakest of the four fundamental forces (e.g., strong, weak, electromagnetic, gravitational), is unimportant when it comes to subatomic distances (Yang 1957; Dirac 1964). The proposed involvement of the gravitational force in binding the two conjugate semiphotons of the binary photon together and in propelling the binary photon through Euclidean space and Newtonian time may provide insight to explore the connection sought by Faraday (1846), Maxwell (1865), and Einstein (Pais 1982) between the gravitational and electromagnetic fields.

If the conjugate semiphotons that constitute the binary photon only had the properties of mass, the binary photon would accelerate to infinite velocity. Consequently, the conjugate particle and antiparticle that make up the binary photon must also have charge that could interact with the electric permittivity (ε_o) and magnetic permeability (μ_o) of the vacuum in

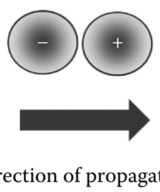

FIGURE 2.3 The propagation of conjugate particles composed of positive and negative mass. The negative mass particle chases the positive mass particle, and the positive mass particle accelerates away from the negative mass particle.

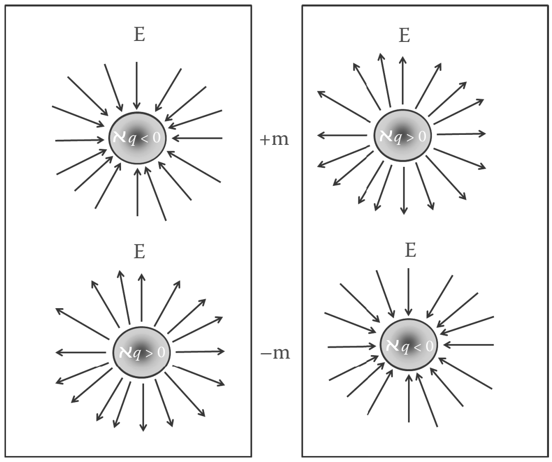

FIGURE 2.4 The electric field lines that radiate from a semiphoton. The two semiphotons on the top have a positive mass and thus are the leading semiphotons. The one on the right has a positive ($\aleph q > 0$) charge and the electric field lines point outwardly, and the one on the left has a negative ($\aleph q < 0$) charge and the electric field lines point inwardly. The two semiphotons on the bottom have a negative mass and thus are the trailing semiphotons. The one on the right has a negative ($\aleph q < 0$) charge and the electric field lines point inwardly, and the one on the left has a positive ($\aleph q > 0$) charge and the electric field lines point outwardly. The two semiphotons on the left are conjugate particles that make one type of binary photon, and the two semiphotons on the right are conjugate particles that make another type.

order to constrain the velocity of the photon to the speed of light (or the reciprocal of the square root of the product of ε_o and μ_o). The existence of charge within a photon seems reasonable since the photon is the carrier of the electromagnetic force. However, the electric field radiating from the charges of the particle and antiparticle must be equal in magnitude and opposite in sign to ensure that the charge of the binary photon is neutral overall (de Broglie 1934d). The direction of the electric field that radiates from a charge depends on both the sign of the charge and the sign of the mass* (Figure 2.4). The gravitational force-induced movement of the charged particles causes a magnetic field according to Ampere's law and an oppositely directed electromotive force according to Faraday's and Lenz's laws that is responsible for reducing the velocity of the binary photon to the speed of light $\left(c = \frac{1}{\sqrt{\varepsilon_o \mu_o}}\right)$. The prophetic Michael Faraday (1846) wrote, "Neither accepting nor rejecting the hypothesis of an ether, or the corpuscular, or any other view that may be entertained of the nature of light; and, as far as I can see, nothing being

* See Wayne (2012c) for the complete equations of symmetry that include a coefficient ℵ that keeps track of the sign of the mass where ℵ is +1 for positive mass and –1 for negative mass. The electric fields generated by the charges cancel when $(\aleph q)m$ of the leading photon equals $(\aleph q)m$ of the trailing photon. In terms of the electric field, a negatively charged electron with negative mass is equivalent to a positively charged electron (positron) with positive mass, and in both cases, the electric field lines point away from the charge.

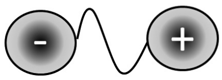

FIGURE 2.5 The positive and negative mass semiphotons oscillate toward and away from the center of gravity as the center of gravity of the binary photon propagates at the speed of light. It is easy to visualize the particle–wave duality when there is not *one* particle but *two* particles that oscillate and can form an oscillating wave. The laws of electromagnetism predict that as the leading particle accelerates away from the negative mass particle as a result of the gravitational force, the leading particle will generate a greater magnetic field, which will produce an electromotive force on itself. This self-induction will put an electromagnetic brake on the leading particle so that the trailing particle can catch up to it. Before the trailing particle catches up to it, the leading particle again accelerates when the gravitational force becomes greater than the electromagnetic braking force that weakens as the leading particle slows down. The combined effects of the gravitational motive force and the electromagnetic braking force result in a longitudinal wave.

really known of a ray of light more than of a line of magnetic or electric force, or even a line of gravitating force."

I assume that the center of gravity of the binary photon, which can be considered to be its rest frame, propagates at the speed of light c along the z-axis as a function of time (Figure 2.5). As a result of the gravitational force on a moving charge inducing an oppositely directed electromotive force, the binary photon may have internal longitudinal motions* that were predicted by Wilhelm Röntgen (1896) and George FitzGerald (1896) and consistent with Einstein's (1909a) "oscillation energy of frequency ν [that] can occur only in quanta of magnitude $h\nu$." Indeed de Broglie (1924) wrote, "Naturally, the light quantum must have an internal binary symmetry corresponding to the symmetry of an electromagnetic wave…." I have described the predicted sinusoidal oscillations with an antisymmetric normal mode using wave equations. The positions of the leading (ϕ_{leading}) and following ($\phi_{\text{following}}$) semiphotons travelling along the z-axis as a function of time is shown in Figure 2.6 and given by the following formulae:

* While the center of gravity of a wave packet moves with a group velocity equal to the speed of light, the particles formed by a wave packet do not all move at the same velocity (de Broglie 1924; French and Taylor 1978). The particles at the front of the wave packet that represent the short wavelengths move with a phase velocity greater than the speed of light, and the particles at the back of the wave packet that represent the long wavelengths move with a phase velocity less than the speed of light. Consequently, the wave packet spreads over time. Also, according to quantum electrodynamics (QED), light has an amplitude to go faster and slower than the vacuum speed of light (Feynman 1985). In a binary photon, the velocities of the semiphotons are greater and less than the speed of light but are coupled in a harmonic oscillator so that the binary photon does not smear out while the center of gravity moves with a velocity equal to the speed of light. The longitudinal oscillation could explain the oscillation in radiation pressure (Einstein 1909b). Longitudinal polarization has been observed experimentally (Wang et al. 2008; Ye et al. 2013).

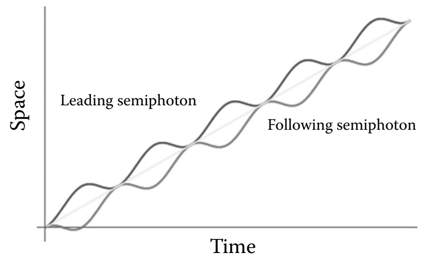

FIGURE 2.6 The longitudinal wave formed by the binary photon moving through space and time. This is a graph of Equation 3.20.

$$\begin{bmatrix} \phi_{\text{leading}}(t) \\ \phi_{\text{following}}(t) \end{bmatrix} = \begin{bmatrix} ct + \frac{\lambda}{4}\left(1-\cos(2\pi\nu t)\right) \\ ct - \frac{\lambda}{4}\left(1-\cos(2\pi\nu t)\right) \end{bmatrix} \left[\hat{z}\right] \tag{2.20}$$

In order for the semiphotons with mass $\left(\frac{\hbar\omega}{2c^2} = \frac{hc}{2\lambda c^2}\right)$ to oscillate in a sinusoidal manner with angular frequency ($\omega = 2\pi\nu$), there must be a restoring force characterized by a spring constant† (K in N/m). The angular frequency of the oscillator is related to the spring constant according to the following formula:

$$\omega = 2\pi\nu = \sqrt{\frac{K}{m}} \tag{2.21}$$

Solving for K, we find that the spring constant that provides the restoring force to the semiphoton is equal to the ratio of a constant ($2\pi^2 hc$) to the cube of the wavelength:

$$K = \frac{2\pi^2 hc}{\lambda^3} \tag{2.22}$$

The longer the wavelength is, the lesser the spring constant becomes, and the more the binary photon approaches a floppy wave. On the other hand, the shorter the wavelength is, the greater the spring constant becomes, and the more the binary photon approaches a *hard* mathematical point. The spring constant‡ is 2.9×10^9 N/m for a 0.01 nm x-ray binary photon, 3921.1 N/m for a 1 nm x-ray binary photon, 6.1×10^{-5} N/m for a

† The spring constant is a one-dimensional property related to flexural stiffness (in N m^2), which is a two-dimensional property that is important for accessing the mechanical properties of the photosynthetic leaf blade and its supporting petiole (Niklas 1992).

‡ As a reference, the spring constant of a binary photon of visible light is similar to the spring constants of the neutrophil microvilli and the elastic cytoplasm, which are 4×10^{-5} N/m (Shao et al. 1998; Hochmuth 2000) and 10^{-5} N/m (Guo et al. 2014), respectively.

400 nm visible binary photon, 2.1×10^{-5} N/m for a 500 nm visible binary photon, 1.8×10^{-5} N/m for a 600 nm visible binary photon, 14.5×10^{-20} N/m for a 3 cm microwave binary photon, and 2.9×10^{-24} N/m for a 1 m radio wavelength binary photon.

The velocities of the leading (v_{leading}) and following ($v_{\text{following}}$) semiphotons along the direction of propagation as a function of time are obtained by differentiating Equation 2.20 and are given by the following formulae:

$$\begin{bmatrix} v_{\text{leading}}(t) \\ v_{\text{following}}(t) \end{bmatrix} = \begin{bmatrix} c + \dfrac{\pi c}{2}\sin(2\pi\nu t) \\ c - \dfrac{\pi c}{2}\sin(2\pi\nu t) \end{bmatrix}[\hat{z}] \quad (2.23)$$

Heretofore, the wave–particle duality of the quantum mechanical photon has been unintuitive. Friedrich Hund (1974) wrote, “one way of explaining quantum theory in physical terms these days consists in regarding it as a completely non-intuitive unification or two intuitive pictures, i.e., classical particles and classical waves of fields.” By considering the photon to be a binary photon composed of two conjugate particles, instead of an elementary particle, it becomes possible to visualize simultaneously the wave and particle nature of the photon or what Arthur Eddington (1928) and Charles Galton Darwin, Charles Darwin’s grandson, called *wavicles*. The simultaneous visualization of the wave-like and particle-like properties was an unrealized goal of Erwin Schrödinger’s (1933) wave mechanics.

The longitudinal wave propagating along the z-axis with a maximal spatial extension of λ and an average spatial extension of $\frac{\lambda}{2}$ is possible if the photon is composed of two particles as opposed to one. Consequently, the binary photons that make up radio waves (1 m–100 km) and microwaves (1 mm–1 m) are predicted to be very long, and binary photons that make up gamma rays (<0.01 nm) and x-rays (0.01–10 nm) are predicted to be very short—approximating a mathematical point. The binary photons that make up the visible light effective in photosynthesis (Engelmann 1882) are predicted to be intermediate in length.

The possibility that a real photon has transverse extension in addition to longitudinal extension comes from an intuitive and mechanical understanding of angular momentum as a mechanical property (Oberg et al. 2000) that means something more than just a number. John Nicholson (1912, 1913) interpreted Planck’s constant as a “natural unit of angular momentum” when he realized that the characteristic absorption and emission spectra of atoms would be intelligible if “the angular momentum of an atom can only rise or fall by discrete amounts when electrons leave or return.”

Niels Bohr (1913) applied Nicholson’s idea of quantized angular momentum to Ernest Rutherford’s (1911) planetary model of the atom and wrote:

> In any molecular system consisting of positive nuclei and electrons in which the nuclei are at rest relative to each other and the electrons move in circular orbits, the angular momentum of every electron round the centre of its orbit will in the permanent state of the system be equal to $h/2\pi$, where h is Planck’s constant.

Realizing that the planets orbited the sun in elliptical orbits as Newton showed was required by a central force, Arnold Sommerfeld (1923) suggested that electrons also orbit the nucleus in elliptical orbits. In addition, Sommerfeld suggested that angular momentum, which was then known as the moment of momentum or impulse moment (Ruark and Urey 1927), must not only characterize the atomic system but also be conserved when the atom emits a photon. Sommerfeld wrote,

> …in the process of emission…, we demanded…the conservation of energy. The energy that is made available by the atom should be entirely accounted for in the energy of radiation ν, which is, according to the quantum theory of the oscillator, equal to $h\nu$. With the same right, we now demand the conservation of momentum and of moment of momentum: if in a change of configuration of the atom, its momentum or moment of momentum alters, then these quantities are to be reproduced entirely and unweakened in the momentum and moment of momentum of the radiation.

The significance of Planck’s constant as a natural unit of angular momentum was also emphasized by Linus Pauling, Sommerfeld’s student. Pauling and E. Bright Wilson Jr. (1935) wrote

> …h, is a new constant of nature; it is called Planck’s constant…Its dimensions (energy × time) are those of the old dynamical quantity called action; they are such that the product of h and frequency ν (with dimensions $\sec^{-1}$) has the dimensions of energy. The dimensions of h are also those of angular momentum, and…just as hν is a quantum of radiant energy of frequency ν, so is $h/2\pi$ a natural unit or quantum of angular momentum.

The selection rules that successfully describe and explain the absorption and emission spectra of atoms and molecules, including chlorophyll, are based on the conservation of angular momentum (Hund 1974; French and Taylor 1978). In the absorption process, a unit of angular momentum is gained by the absorber, and in the emission process, a unit of angular momentum is lost by the emitter. While the unit of angular momentum carried to or carried away from the substance has a magnitude of $\hbar$, the direction reverses, and thus the sign of the angular momentum changes, between absorption and emission.

What would the radius of the binary photon be in order for it to have its observed angular momentum? While this question cannot be answered using current quantum mechanics (Landau and Lifshitz 1958), to answer this question, I went back to Niels Bohr’s correspondence principle, which sets a classical quantity equal to a quantum quantity. Classically, the angular momentum of a particle is equal to $mvr\Gamma$, where m is the mass of body, v is its angular velocity, r is its radius, and

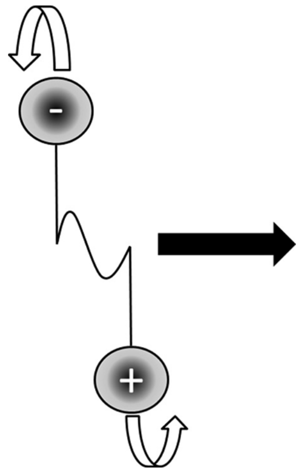

FIGURE 2.7 The rotational motion of the semiphotons is superimposed on the oscillating translational motion.

Γ is a dimensionless geometric factor between 0 and 1 that equals 1 for a point mass at the end of a massless string of radius *r*. For simplicity (and no better reason), I will let Γ = 1, which describes the movement of a mass at the end of a massless string. The rotational motion will be superimposed on the oscillating translational motion (Figure 2.7).

The mass of each semiphoton that composes the binary photon is one-half of the total mass of the binary photon and is given by

$$m = \frac{h\nu}{2c^2} \tag{2.24}$$

Using the correspondence principle where *v* is the angular velocity and *r* is the radius of each semiphoton that composes the binary photon, we get

$$L = \frac{\hbar}{2} = \frac{h}{4\pi} = mvr \tag{2.25}$$

for a semiphoton with angular momentum equal to $\frac{\hbar}{2}$.

We can calculate the radius of the semiphoton from Equation 2.25 by letting $v = 2\pi\nu r$ and inserting the mass $m = \frac{h\nu}{2c^2}$ of that semiphoton to get

$$\frac{h}{4\pi} = \frac{h\nu}{2c^2} 2\pi\nu r^2 \tag{2.26}$$

After cancelling and rearranging, we get

$$r^2 = \frac{c^2}{(2\pi)^2 \nu^2} \tag{2.27}$$

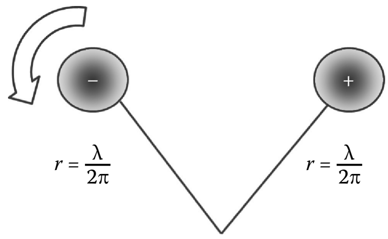

FIGURE 2.8 The radius of the binary photon can be determined from the angular momentum of the binary photon (ħ), the angular momentum of the semiphoton $\left(\frac{\hbar}{2}\right)$, the mass of the binary photon $\left(\frac{h\nu}{c^2}\right)$, and the mass of a semiphoton $\left(\frac{h\nu}{2c^2}\right)$ using the correspondence principle.

Since according to the dispersion relation, $\frac{c^2}{\nu^2} = \lambda^2$, we get

$$r^2 = \frac{\lambda^2}{(2\pi)^2} \tag{2.28}$$

And after taking the square root of both sides, we get

$$r = \frac{\lambda}{2\pi} \tag{2.29}$$

That is, the radius of the binary photon is equal to the wavelength of light divided by 2π (Figure 2.8), and the circumference (2π*r*) is equal to the wavelength. The radius of the binary photon is identical to the radius of the semiphoton, since for the binary photon, the angular momentum is equal to $\frac{h}{2\pi}$ and the mass is equal to $\frac{h\nu}{c^2}$. The diameter (*d*) of a cylinder- or needle-like binary photon is approximately equal to one-third of its wavelength*:

$$d = 2r = \frac{\lambda}{\pi} = 0.32\lambda \tag{2.30}$$

This equation, which is based on the strong assumptions that the binary photon has energy, linear momentum, and angular momentum, all of which have mechanical consequences, and the arbitrary assumption concerning the geometry of the binary photon, describes the transverse extension or *bigness* of a binary photon with a given wavelength. Likewise, J. J. Thomson (1925) proposed that the photon was a vibrating ring-shaped Faraday *tube of force* where the circumference was equal to the wavelength of light and the diameter of the ring was equal to $\frac{\lambda}{\pi}$. Although I hope to elucidate the form of the binary photon eventually, the arbitrariness

* This explains why the lateral resolution of optical systems, including those used for superresolution microscopy, is approximately three times greater than the axial resolution (Wayne 2014a).

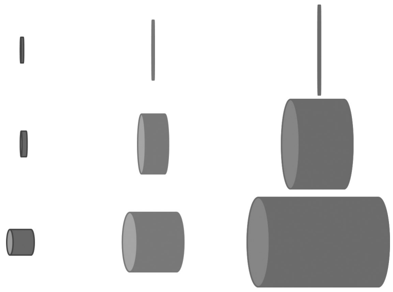

FIGURE 2.9 The predicted three-dimensional forms and relative sizes of oscillating binary photons with a wavelength of 400 nm (left), 500 nm (center), and 600 nm (right).

of the geometrical assumption probably does not introduce a great error since by considering the photon to be a single Newtonian corpuscle, and using similar reasoning, Zu (2008) calculated the diameter of a photon to be 0.5 λ. Previously, Ludwik Silberstein (1922; Mees 1922; Silberstein and Trivelli 1922) obtained a similar diameter by modeling the interaction of photons with photographic silver grains, and Bo Lehnert (2006, 2008, 2013) also derived a similar diameter by revising the assumptions of quantum electrodynamic theory.

When the wavelength of a binary photon approaches zero, so does its diameter, and the *bigness* of the binary photon, or perhaps its smallness, approaches the size of a mathematical point. When the wavelength of a binary photon approaches infinity, so does its diameter, and the *bigness* of the binary photon approaches infinity and can be described as an infinite plane wave. A binary photon of monochromatic 500 nm light has an *average* length of 250 nm and a diameter of 159.2 nm. This is why two *close* binary photons can interfere or a single binary photon can interfere with itself. The *bigness* of a binary photon with a wavelength of 400 nm is smaller; and the *bigness* of a binary photon with a wavelength of 600 nm is larger than the bigness of a binary photon with a wavelength of 500 nm (Figure 2.9).

The size of a photon can be used to derive Planck's blackbody radiation law (Shanks 1956) where real space replaces phase space. Support for the predicted three-dimensional size of the binary photon, in which the radius and average length are given by $\frac{\lambda}{2\pi}$ and $\frac{\lambda}{2}$, comes from the ability to predict the relationship between the number densities of photons of given wavelengths and the temperature of a blackbody cavity with a constant volume (Wayne 2014b*).

In order for the binary photon to have a nonvanishing angular momentum that is equal to $\frac{h}{2\pi}$, the two semiphotons, with masses of opposite signs, have to rotate perpendicular to the axis of propagation with opposite senses. Using the calculated radius, I have incorporated the rotation of the two semiphotons that make up the binary photon into the wave equation that describes the time-varying positions (ϕ) of the two semiphotons:

$$\begin{bmatrix} \phi_{\text{leading}}(t) \\ \phi_{\text{following}}(t) \end{bmatrix} = \begin{bmatrix} \frac{\lambda}{2\pi}\cos(2\pi\nu t) & -\frac{\lambda}{2\pi}\sin(2\pi\nu t) & ct+\frac{\lambda}{4}(1-\cos(2\pi\nu t)) \\ -\frac{\lambda}{2\pi}\cos(2\pi\nu t) & -\frac{\lambda}{2\pi}\sin(2\pi\nu t) & ct-\frac{\lambda}{4}(1-\cos(2\pi\nu t)) \end{bmatrix} \begin{bmatrix} \hat{x} \\ \hat{y} \\ \hat{z} \end{bmatrix} \tag{2.31}$$

The positions of the two semiphotons with respect to time as they spiral along the propagation axis are shown in Figure 2.10. The velocities (v) of the semiphotons with respect to time are given by the following formulae:

$$\begin{bmatrix} v_{\text{leading}}(t) \\ v_{\text{following}}(t) \end{bmatrix} = \begin{bmatrix} -c\sin(2\pi\nu t) & -c\cos(2\pi\nu t) & c+\frac{\pi c}{2}\sin(2\pi\nu t) \\ c\sin(2\pi\nu t) & -c\cos(2\pi\nu t) & c-\frac{\pi c}{2}\sin(2\pi\nu t) \end{bmatrix} \begin{bmatrix} \hat{x} \\ \hat{y} \\ \hat{z} \end{bmatrix} \tag{2.32}$$

The motions of the semiphotons are evocative of Maxwell's (1861) mechanical interpretation of the luminous ether composed of particles and vortices. The binary photon is also reminiscent of two vibrating rings or strings moving through an observable Euclidean space and Newtonian time. The binary photon has been described as a three-dimensional version of string theory. Actual string theory, according to Michio Kaku (1994), expounds that "the laws of nature become simpler and more elegant when expressed in higher dimensions." Kaku writes

> String theory is such a promising candidate for physics because it gives a simple origin of the symmetries found in particle physics as well as general relativity…The heterotic string consists of a closed string that has two types of vibrations, clockwise and counterclockwise, which are treated differently. The clockwise vibrations live in a ten-dimensional space. The counterclockwise live in a 26-dimensional space, of which 16 dimensions have been compactified… The heterotic string owes its name to the fact that the clockwise and the counterclockwise vibrations live in two different dimensions but are combined to produce a single superstring theory. That is why it is named after the Greek word for heterosis, which means 'hybrid vigor.'

The biophysical approach to nature assumes that a form–function relationship exists. Although this is not necessarily true (Niklas and Spatz 2012), the biophysicist in me thinks that the structure of the binary photon has hybrid vigor in performing the function of electromagnetic energy transfer from the sun to the chloroplast through Euclidean space and Newtonian time.

Since photons are the carrier of the electromagnetic force (Fermi 1932), it is only natural that they generate electric

* Although the final equation given in Wayne (2014b) is correct, there is a factor of 2 error in calculating the cross-sectional area of a photon that was cancelled out by unnecessarily taking the polarization of the photon into consideration.

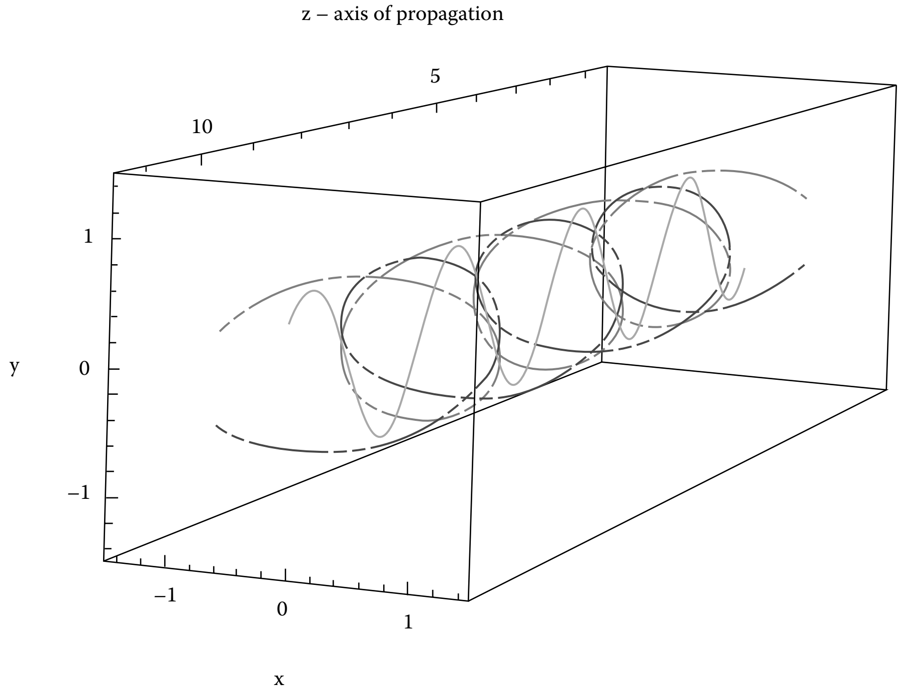

FIGURE 2.10 The anatomy of the binary photon showing the positions of the leading (dashed dark line) and following (dashed light line) semiphotons that compose a binary photon with respect to time as predicted by Equation 3.31. The solid line is the mean position of the two semiphotons.

and magnetic fields described by Faraday's, Ampere's, and Lenz' laws (Jackson 1999). Since the two semiphotons carry charge ($\aleph q$), Coulomb's law predicts that they each generate a time-varying, three-dimensional electric field ($\mathfrak{E}$) inside the binary photon. Positively charged particles ($\aleph q > 0$) generate electric fields that point away from the source, while negatively charged particles ($\aleph q < 0$) generate electric fields* that point toward the source.

The electric field can be calculated from the addition of the principal inward normal unit vectors from each semiphoton. As the two conjugate particles of the binary photon rotate, their electric fields are superimposed inside and diverge outside the binary photon. This geometry ensures quantization of a real time-varying electric field in real space. At 0° (N) and 180° (S), the electric field vectors inside the binary photon destructively interfere and at 90° (E) and 270° (W), the electric field vectors inside the binary photon constructively interfere to give a linearly polarized wave equivalent to Faraday's (1846) *line of electric force*. I claim that, in the binary photon, only linearly polarized light can result from the two charges with opposite polarity rotating with opposite senses. By contrast, Dirac (1958) claimed that the electric field of a single photon was circularly polarized. This is a testable difference between the model of the binary photon and the quantum mechanical point-like photon. The azimuth of polarization of the electric field of the binary photon depends on the azimuth of the line between the two particles of the binary photon when they are maximally separated and the dipole moment is greatest. The transverse electric field in the x–y plane is not confined to one point along the y-axis but oscillates up and down along the y-axis (Figure 2.11) osculating perpendicular to the solid curve shown in Figure 2.10. This is the three-dimensional extension of Maxwell's (1873) planar electric wave. Consistent with the wave theory of light, the electric fields of two binary photons constructively or destructively interfere in a manner that depends on the phase of the three spatial components of each binary photon. Each linearly polarized binary photon has at least two isomers—one with a parallel magnetic moment and one with an antiparallel magnetic moment (see below). Perhaps entanglement (Ismail et al. 2014) is related to racemic mixtures of binary photons.

While the positions of the semiphotons determine the polarization of the electric field, the velocities (v) of the semiphotons determine the polarization of the magnetic field ($\mathfrak{B}$). The three-dimensional form of the magnetic field of the binary photon depends on the time-varying three-dimensional velocities, which can be determined relative to the principal unit tangent vectors of the two moving charges. Because the products of the charge and the velocity of each conjugate semiphoton have the same sign, the magnetic fields they generate add together. The superposition of the magnetic fields is maximal in the y–z plane. The magnetic field oscillates perpendicular to the electric field, being greatest when

* Coulomb's law only applies to a mathematical point that cannot blow apart. Assuming that the semiphotons are not mathematical points, and the circumference has width, we ask in the spirit of Henri Poincaré, what stops the charge of a semiphoton from repelling itself and splitting into fragments? I assume that the charge is indivisible and that the mass of the charged particle provides the Poincaré force necessary to hold the charge within a small volume. As a result, the electrical potential decreases exponentially with distance in a manner analogous to the Yukawa potential (de Broglie 1962).

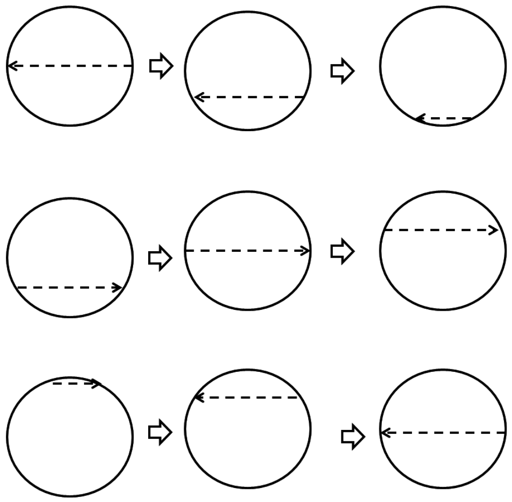

FIGURE 2.11 Transverse sections of a binary photon over time. The azimuth of polarization of the electric field (dashed line) of the binary photon is determined from the superposition of the electric field vectors of the two conjugate particles that make up the binary photon. The electric dipole moment is greatest when the two semiphotons are maximally separated in the *x*–*y* plane and minimally separated in the *y*–*z* plane. The transverse electric field in the *x*–*y* plane is not confined to one point on the *y*-axis but oscillates up and down the *y*-axis. The plane of the oscillating electric field is perpendicular to the solid sinusoidal curve shown in Figure 2.10.

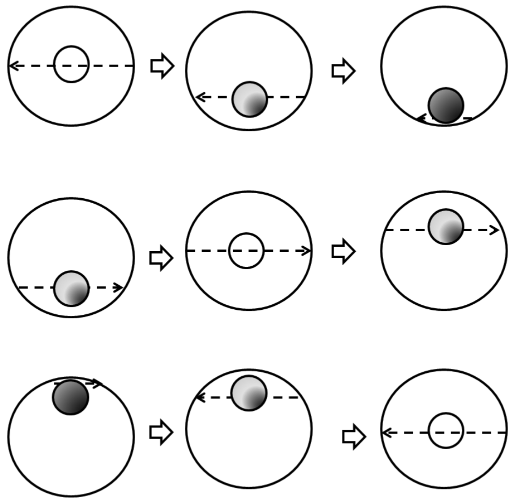

FIGURE 2.12 Transverse sections of a binary photon over time. The magnetic field formed by the superposition of the magnetic fields generated by the two semiphotons is orthogonal to the electric field and oriented either parallel or antiparallel to the axis of propagation. The strength of the magnetic field is indicated by the relative darkness of the circles. The oscillating magnetic field in the *y*–*z* plane is parallel to the plane of the yellow sinusoid curve shown in Figure 2.10. The electromagnetic field is quantized inside the binary photon, and the strength of the magnetic field alternates in time with the electric field. The electric dipole moment is weakest when the magnetic dipole moment is strongest. This occurs when the two semiphotons are minimally separated in the *x*–*y* plane and maximally separated in the *y*–*z* plane. The Poynting vector, or the flux of energy density, is obtained by rotating the right hand from the plane of the electric field to the plane of the magnetic field.

the electric dipole moment is weakest and weakest when the electric dipole moment is greatest (Figure 2.12). The magnetic field of the binary photon is a three-dimensional extension of Maxwell's (1873) planar magnetic wave that was predicted by Evans and Vigier (1994). The Poynting vector, which directly gives the energy density flux and from which the radiation pressure can be derived, can be obtained for the binary photon from the principal planes of the electric and magnetic fields using the right-hand rule. The three-dimensional magnetic field may be useful in explaining the effects of magnets on light (Weinberger 2008).

After finding an effect of magnetism on the azimuth of polarization of light propagating through glass, Faraday (1846) wrote

> Thus is established, I think for the first time, a true, direct relation and dependence between light and the magnetic and electric forces; and thus a great addition made to the facts and considerations which tend to prove that all natural forces are tied together, and have one common origin…the powers of nature is…manifested by particular phenomena in particular forms, is here further identified and recognized, by the direct relation of its form of light to its forms of electricity and magnetism.

Michael Faraday (see Thompson 1901), John Kerr (1877, 1878), Pieter Zeeman (1903), and others (Rikken and van Tiggelen 1996; 't Hooft and van der Mark 1996; van Tiggelen and Rikken 2002) found that a magnetic field could influence the polarization of light, but it is not clear whether the magnet acts on the light itself and/or on the electrons of the material that influence the propagation of light. On the other hand, Röntgen (1896) found that x-rays were not deflected by a magnet and used the fact that cathode rays but not x-rays could be bent by a magnetic field to distinguish the newly discovered x-rays from cathode rays. This distinction was also used by George P. Thomson (1928, 1938) to confirm that the diffraction pattern he saw was due to electrons and not x-rays. Does the fact that the deflection of x-ray was not detected mean that x-rays do not have a magnetic moment? Should the results be extrapolated to mean that photons do not have a magnetic moment? It could be argued *a priori* that as the carrier of the electromagnetic force, the photon should have a magnetic moment, and based on their analysis of a gamma photon produced by the annihilation of an electron and a positron, Sahin and Saglam (2009) derived a formula to calculate the magnetic moment of a photon. Although the photon is usually supposed to lack a magnetic moment (Jackson 1999; Karpa and Weitz 2006; Altschul 2008), this may be an unjustified and unintended consequence of the assumption that the photon is a massless $\left(m = \frac{\hbar\omega}{c^2} = 0\right)$ mathematical point. Using the model of the binary photon, I predict that all photons have a magnetic moment, and the formula I derive below is identical to that derived by Sahin and Saglam (2009).

According to the model of the binary photon, the magnetic moment (μ) of a semiphoton with charge ($\aleph q$) and mass $\left(\frac{\hbar\omega}{2c^2}\right)$ is related to its angular momentum $\left(\frac{\hbar}{2}\right)$ by the following equation:

$$\mu = \frac{\aleph q}{2m} L = \frac{\aleph q}{2m}\frac{\hbar}{2} = \frac{\aleph q \hbar 2c^2}{4\hbar\omega} = \frac{\aleph qc^2}{2\omega} \quad (2.33)$$

Since the conjugate particles that make up a binary photon have opposite charge ($\aleph q$) and opposite spinning frequency (ω), then $\frac{\aleph qc^2}{2\omega} = \frac{\aleph qc^2}{2\omega}$ for the leading and trailing semiphotons, respectively. Thus, the magnetic moment for the binary photon does not vanish; but it is twice as great as the magnetic moment of each individual particle. The magnetic moment (μ) of the binary photon is equal to

$$\mu = \pm\left|\frac{\aleph qc\lambda}{2\pi}\right| = \pm\left|\frac{\aleph qc^2}{\omega}\right| \quad (2.34)$$

The orientation of the magnetic moment depends on the composition of the binary photon (Table 2.1). When the leading semiphoton with positive mass has a positive charge ($\aleph q > 0$) and a clockwise spin (the trailing semiphoton would have a negative mass, a negative charge [$\aleph q < 0$], and an anticlockwise spin), the magnetic moment is antiparallel to the vector of propagation (Class I), and when the leading semiphoton with positive mass has a negative charge ($\aleph q < 0$) and a clockwise spin (the trailing semiphoton would have a negative mass, a positive charge [$\aleph q > 0$], and an anticlockwise spin), the magnetic moment is parallel to the vector of propagation (Class II). Both of these binary photons (Classes I and II) have an angular momentum that is antiparallel to the axis of propagation. Symmetry predicts that there may also be two other binary photons with an angular momentum that is parallel to the axis of propagation (Classes III and IV). However, it is also possible that for binary photons that travel at the speed of light, nature favors one isomer over the other as it does in the case of neutrinos and antineutrinos. All neutrinos have left-handed helicity with spin antiparallel to the propagation axis, and all antineutrinos have right-handed helicity with spin parallel to the propagation axis (Lee 1957; Lee and Yang 1957; Goldhaber et al. 1958; Griffiths 1987; Solomey 1997; Bilenky 2013).

Equation 2.34 predicts that the magnetic moment of a binary photon is proportional to the wavelength and inversely proportional to the angular frequency. The magnetic moment of a binary photon with a wavelength of 0.01 nm is 7.61×10^{-23} A m^2; the magnetic moment of a binary photon with a wavelength of 400 nm is 1.45×10^{-21} A m^2; the magnetic moment of a binary photon with a wavelength of 500 nm is 1.81×10^{-21} A m^2; the magnetic moment of a binary photon with a wavelength of 600 nm is 2.17×10^{-21} A m^2; and the magnetic moment of a binary photon with a wavelength of 1 m is 8.62×10^{-14} A m^2.

The predicted proportional relationship between the magnitude of the magnetic moment and the wavelength indicates that long wavelength binary photons are more likely to be bent by a magnetic field than x-rays. However, symmetry predicts that a beam of natural light with both parallel and antiparallel magnetic moments will be broadened by a magnetic field, while a beam with only one orientation of the magnetic moment will be bent (Figure 2.13). Perhaps the x-rays observed by Röntgen were broadened but not bent. Experimental tests of the magnetic moment of light could reify or falsify the model of the binary photon.

TABLE 2.1
Four Possible Classes of Binary Photons

Class	Symmetry	Leading Semiphoton	Following Semiphoton	Angular Momentum (L)	Magnetic Moment (μ)
I	M	+m	–m	Antiparallel	Antiparallel
	C	ℵq > 0	ℵq < 0		
	P	CW	ACW		
II	M	+m	–m	Antiparallel	Parallel
	C	ℵq < 0	ℵq > 0		
	P	CW	ACW		
III	M	+m	–m	Parallel	Parallel
	C	ℵq > 0	ℵq < 0		
	P	ACW	CW		
IV	M	+m	–m	Parallel	Antiparallel
	C	ℵq < 0	ℵq > 0		
	P	ACW	CW		

Note: Mass (M), charge (C), parity (P), clockwise (CW), and anticlockwise (ACW). Parallel and antiparallel is relative to the propagation vector.

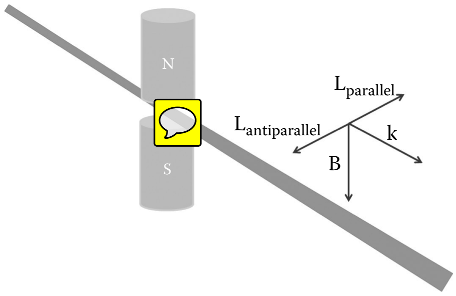

FIGURE 2.13 Predicted effect of a magnetic field on binary photons. If the binary photon has a magnetic moment, a magnetic field will induce a torque on it. The torque exerted on the binary photon will depend on the orientation of the magnetic moment. As a result of the magnetic field, there will be a broadening of the beam in the direction parallel or antiparallel to the magnetic field lines.

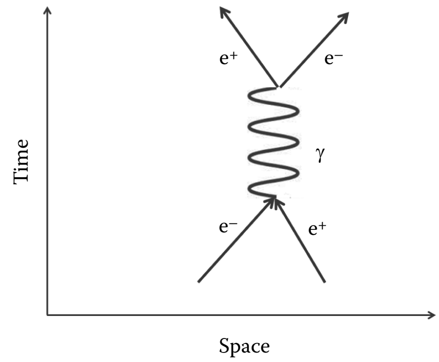

FIGURE 2.14 Feynman diagram of the annihilation of an electron (e^-) and positron (e^+) to form a gamma ray photon (γ) and the production or creation of an electron and a positron from a gamma ray photon.

Eugene Wigner (1967) assumed that elementary particles were symmetrical in terms of right and left. Lee and Yang (1956) questioned the assumption that parity was a conserved quantity, and Wu et al. (1957) and Garwin et al. (1957) showed that parity was not a conserved quantity.

In the standard model of physics, symmetry includes real particles of matter, real particles of antimatter, and the virtual particles that pop in and out of the vacuum (Lee 1988). In order to balance the positive energy of matter and antimatter, the vacuum was endowed by Dirac (1930) with an infinite number of particles with negative energy that could give rise to virtual particles (Feynman 1949a,b, 1987). "A virtual particle," according to David Kaiser (2005), "is one that has borrowed energy from the vacuum, briefly shimmering into existence literally from nothing. Virtual particles must pay back the borrowed energy quickly, popping out of existence again, on a time scale set by Werner Heisenberg's uncertainty principle." The uncertainty principle, according to quantum field theory, allows photons to develop internal structures that give rise to fermion–antifermion pairs for a short period of time that carry the same quantum numbers as the photon itself (Przybycień 2003; Lehnert 2008). Perhaps each binary photon propagating through an empty and vacuous vacuum is actually composed of a fermion–antifermion pair that conserves the energy, linear momentum, and angular momentum of the binary photon and can be produced when the binary photon experiences an electric field that is great enough to split it. If so, the binary photon serves as "a unification between the charges (and thus of the forces) by…a single entity, of which the various charges are components in the sense that they can be transformed one into the other" (Salam 1979).

Indeed, pair production is known to occur when a photon with a very short wavelength enters the strong electric field of an atom (Figure 2.14). During pair production, a photon (γ) with energy of 1.02 MeV undergoes an internal conversion to form an electron (e^-), which is a particle, and a positron (e^+), which is an antiparticle (Curie and Joliot 1933; Rose and Uhlenbeck 1935; Leone and Robotti 2010). Pair production, in general, results when a photon with sufficient energy ($\geq 2mc^2$) is transformed into a particle (mc^2) and its antiparticle (mc^2) both measured by detectors made of matter to have mass *m*. Conversely, when an antiparticle such as a positron collides with a particle such as an electron, they annihilate each other and are transformed into high-energy photons in a process known as pair annihilation. Positrons are not *other-worldly* and have been used to visualize photosynthesis in the leaves of *Cannabis sativa* (Kawachi et al. 2006).

It turned out that CPT, the product of the signs of charge (C), parity (P), and time (T), was a conserved quantity (Lee 1988). Wayne (2012c) suggested that the sign of mass (M) might be a more realistic indicator than the sign of time, and it is CPM not CPT that is conserved. CPM theory allows all symmetries to be satisfied with real particles of matter and real particles of antimatter and a vacuum that has been swept clean of everything except its electric permittivity and magnet permeability.

The photon, according to the standard model of physics, is a gauge boson that carries the electromagnetic force (Glashow 1979; Salam 1979; Weinberg 1979). The binary photon could be considered to be a boson with spin ±1 composed of two conjugate fermions with spin ±1/2 (de Broglie 1934d).

I claim that the photon cannot be a mathematical point since the presence of two rotating particles ensures that the binary photon is longer and wider than a mathematical point. The extension allows the formation of an electric dipole moment ($\pm|\aleph q\lambda|$) and a magnetic moment $\left(\pm\left|\frac{\aleph q\lambda c}{2\pi}\right|\right)$, two characteristics that I presume are necessary for the carrier of the electromagnetic force. The model of the binary photon follows Franks Lloyd Wright's (1953) dictum *Form and Function Are One*, which was inspired by his love of design and experience with the natural world.

Robert Hooke (1665) learned long ago that a mathematical point is an idealization that is not found in nature. He wrote in his *Micrographia*,

> As in Geometry, the most natural way of beginning is from a Mathematical point; so is the same method in Observations and Natural history the most genuine, simple, and instructive….

> And in Physical Enquiries, we must endevour to follow Nature in the more plain and easie ways she treads in the most simple and uncompounded bodies, to trace her steps, and to be acquainted with her manner of walking there, before we venture our selves into the multitude of meanders she has in bodies of a more complicated nature; lest, being unable to distinguish and judge our way, we quickly lose both Nature our guide, and our selves too, and are left to wander in the labyrinth of groundless opinions; wanting both judgment, that light, and experience, that clew, which should direct our proceedings. We will begin these our Inquiries therefore with the Observations of Bodies of the most simple nature first, and so gradually proceed to those of a more compounded one. In prosecution of which method, we shall begin with a Physical point; of which the Point of a Needle is commonly reckon'd for one; and is indeed, for the most part, made so sharp, that the naked eye cannot distinguish and parts of it…. But if view'd with a very good Microscope, we may find that the top of a Needle…appears a broad, blunt, and very irregular end….

Indeed, Einstein (in Campos 2004) wrote to Hendrik Lorentz in 1909 stating that, "I am not at all of the opinion that one should think of light as being composed of mutually independent quanta localized in relatively small spaces."

Just as a plant systematist has to weigh the advantages and disadvantages of lumping two taxa into one taxon or splitting one taxon into two, so must the biophysical plant biologist weigh the value and limitations of the binary photon and the quantum mechanical, mathematical point-like photon as the carrier of the electromagnetic force that separates charge in the reaction center that results in the evolution of oxygen and the fixation of carbon dioxide, two key events that make the contemplation of the photon possible.

2.4 UNCERTAINTY PRINCIPLE

The uncertainty principle originated when Werner Heisenberg (1927) realized the difficulty one would have trying to use just one photon to determine the position and momentum of a subatomic particle such as an electron at an instant in time without disturbing it. Pierre-Simon Laplace (1814) had written,

> We ought then to regard the present state of the universe as the effect of its anterior state and as the cause of the one which is to follow. Given for one instant an intelligence which could comprehend all the forces by which nature is animated and the respective situation of the beings who compose it an intelligence sufficiently vast to submit these data to analysis it would embrace in the same formula the movements of the greatest bodies of the universe and those of the lightest atom; for it, nothing would be uncertain and the future, as the past, would be present to its eyes.

Knowledge of the position and momentum of an electron would allow a Laplacian super being to predict all future movements of the electron with deterministic physical laws. The fundamental nature of chance and statistics given by the uncertainty principle of quantum mechanics would not allow such determinism in Euclidean space and Newtonian time (Jordan 1927; Heisenberg 1933, 1974; Frayn 2000). Ralph Lillie (1927), Eddington (1928), Bohr (1934), Compton (1935), Dingle (1937), Schrödinger (1945), Heitler (1963), Hawking and Mlodinow (2010), and Heisenberg's son Martin Heisenberg (2009) have discussed the relationship between physical indeterminism and the beliefs in free will and the freedom of the human mind. To me, free will is a fact (Wayne 2010c), and the determinacy found in the binary photon suggests that the source of free will must be sought outside of quantum mechanics.

In principle, the electron can be localized best with a microscope by using the shortest wavelength of the illuminating gamma rays. However, as $\lambda \to 0$, the hard gamma ray photons, with great linear momentum, send the electron flying, disturbing its location. On the other hand, if one observed the subatomic particle with soft gamma rays with longer wavelengths, the electron would not be as disturbed, but as a result of diffraction, the localization would be coarser. Likewise the linear momentum of the moving electron can be determined by measuring the Doppler shift of the scattered gamma rays as described by the Compton effect. But to get the most accurate measure of the electron's linear momentum, short wavelength gamma rays, which give the greatest Doppler shift, should be used. However, the short wavelength gamma rays cause great recoil and disturb the original position of the electron. One could determine the linear momentum with softer gamma rays with longer wavelength, which do not disturb the electron as much, but the Doppler shift is reduced and the linear momentum measurement like that for the position will be less sharp. It is impossible to accurately measure the position and linear momentum of an electron at the same time, and thus, the description of a quantum system at a given instant of time is accurately described by a smaller number of quantities than a classical system, where differential equations can be used to determine the instantaneous velocity of a particle at a given position.

The uncertainty is a consequence of the particulate nature of light because even one photon, the minimum unit possible, disturbs the localization and linear momentum of an electron (Bohr 1928; Heisenberg 1930; Darwin 1931; Hawking 1999). Heisenberg (1927) realized that the mutually incompatible requirement for longer and shorter wavelengths is a general principle that results in incomplete knowledge of the electron in principle. Since position and linear momentum were two canonically linked variables in quantum mechanics, he suggested that there was a fundamental limit to knowledge. Heisenberg (1927) wrote, "At the instant of the determination of its position—i.e., the instant at which the light quantum is diffracted by the electron—the electron discontinuously changes its impulse. That change will be more pronounced, the smaller the wavelength of the light used, i.e., the more precise the position determination is to be." That is, the measurement of position disturbs the simultaneous measurement of linear momentum.

To describe the reciprocal relationship between the canonical variables of quantum mechanics that result in incomplete knowledge, Heisenberg introduced the principle of *Umbestimmtheit*, which could stand for the principle of indeterminacy, indefiniteness, or uncertainty in the following forms (Ruark and Urey 1930; Pauling and Wilson 1935; Mott and Sneddon 1948):

$$\Delta p \Delta z \sim h \tag{2.35}$$

and

$$\Delta p \Delta z = \hbar \tag{2.36}$$

Subsequently, the uncertainty relation has been presented in alternative but not equivalent forms such as

$$\Delta p \Delta z \geq \frac{\hbar}{2} \tag{2.37}$$

where the relationship is derived from the mathematical structure of the quantum theory, and Δ represents the uncertainty due to the standard deviation (Kennard 1927: Richtmyer and Kennard 1942, 1947; Richtmyer et al. 1955, 1969; Brehm and Mullin 1989; Griffiths 2005; Serway et al. 2005), and

$$\Delta p \Delta z = h \tag{2.38}$$

where Δ represents the uncertainty due to the wave nature of light (Slater and Frank 1933; Slater 1951; Brehm and Mullin 1989; Serway et al. 2005).

The uncertainty principle, which replaced the principle of causality, undergirds the principle of complementarity touted by Bohr's (1934) Copenhagen School that treats quantum mechanics as a complete theory and emphasizes the particle-like *or* wave-like properties of light and the necessity of chance. By contrast, the binary photon is a melting pot for particle(s)-like *and* (as opposed to *or*) wave light properties that welcomes causality. The unity in diversity displayed in the binary photon provides a way of describing the heretofore hidden variables (Bohm 1952a,b; Bohm and Vigier 1954) within the photon that would seem to cause a mathematical point-like photon to scatter in a probabilistic manner. De Broglie (1957) wrote

> It is possible that looking into the future to a deeper level of physical reality we will be able to interpret the laws of probability and quantum physics as being the statistical results of the development of completely determined values of variables which are at present hidden from us.

The way the transverse electric and longitudinal magnetic fields oscillate above and below the axis of propagation is one such hidden variable. In this way, the binary photon provides a challenge to the fundamental nature of the principle of uncertainty, the principle that has led to the counterintuitive elevation of chance and the promotion of paradoxical interpretations of reality supported by the maxim *shut up and calculate* (Mermin 1989, 2004; Tegmark 2007). Indeed, Eddington (1928) wrote that "if we could understand it [$qp - pq = \frac{ih}{2\pi}$, the root of the Uncertainty Principle] we should not think it so fundamental."

The time-varying position and extension of the binary photon may provide the hidden variables that allow the complete description of a process. A precisely defined state of the linear momentum* and the position of the binary photon can be calculated in principle from Equations 2.31 and 2.32 and the initial conditions. The product of the velocity variation $\left(\frac{\pi c}{2} + \frac{\pi c}{2} = \pi c\right)$ along the axis of propagation of the binary photon and its mass $\left(\frac{hc}{\lambda c^2}\right)$ gives its variation in linear momentum $\left(\Delta p = \left(\Delta \frac{hc}{\lambda c^2} \pi c\right)\right)$. The product of the variation in linear momentum and the variation in the length ($\Delta z = \Delta\lambda$) of the binary photon along the axis of propagation results in an equation comparable to the uncertainty relation:

$$(\Delta\lambda)\left(\Delta \frac{hc}{\lambda c^2} \pi c\right) = \pi h \tag{2.39}$$

Since the two rotating semiphotons are in a plane including the propagation axis only twice during a cycle $\left(\frac{2}{2\pi}\right)$, then the product of the length variation and the momentum variation in the plane that includes the axis of propagation is

$$(\Delta\lambda)\left(\Delta \frac{hc}{\lambda c^2} \pi c\right)\left(\frac{2}{2\pi}\right) = h \tag{2.40}$$

If Δλ is related to the electric field and $\Delta \frac{hc}{\lambda c^2} \pi c$ is related to the magnetic field, it may be possible to visualize the hidden variables experimentally by mapping the electric and magnetic fields in a standing wave formed in Lecher (1890) wires. In principle, a linear wire antenna could be used to map the electric field, and a circular wire loop antenna could be used to map the magnetic field of a binary photon.

Could a knowledge of the phase of the binary photon, which is in principle knowable, tell us how much of the momentum of an incident photon will be transferred to an electron whose position is being located (McQuarrie et al. 2010)? Could the phase of the binary photon, which is in principle knowable,

* The direction of the linear momentum vector depends on the sign of the mass of the semiphoton and its velocity. Thus, oscillating semiphotons in a binary photon have linear momentum vectors that point in the same direction at any given time during the oscillation. The linear momentum increases as the semiphoton with positive mass moves in the direction of propagation and decreases as the semiphoton with positive mass moves antiparallel to the direction of propagation. In order for linear momentum to be conserved in a harmonic oscillator, the *kinetic* linear momentum must be transformed into *potential* linear momentum (~ the spring constant) just as the kinetic energy is transformed into potential energy.

determine whether a photon is reflected from or transmitted through an interface (Feynman 1985)? Could the phase of the two semiphotons be the hidden variables proposed by Max Born (1926), long-searched for, and often poo-pooed (von Neumann 1932; Bohm 1957; Belinfante 1973; Pinch 1977; Peat 1997)? Such an interpretation would provide support for the idea that Heisenberg's (1927) uncertainty principle is not a foundational principle that "once and for all establishes the invalidity of the law of causality." Schrödinger (in Heisenberg 1927) described "quantum mechanics as a formal theory of frightening, even revulsive un-intuitiveness and abstraction." The calculable and predictive but paradoxical nature of quantum mechanics may, in part, result from considering the photon as a mathematical point-like elementary particle subject to statistical laws that hide important *real-world* parameters instead of a pair of particles, with theoretically knowable time-varying momenta and distance, and electric and magnetic fields that interact causally with matter. Thus, even though the act of observation would have an effect on atomic and subatomic particles (Park 1992), the cause and effect relation could be knowable in principle. Perhaps this is what Einstein meant when he wrote to Born (2005) on December 4, 1926: "Quantum mechanics is certainly imposing. But an inner voice tells me that it is not yet the real thing. The theory says a lot, but does not really bring us any closer to the secret of the 'old one.' I, at any rate, am convinced that He is not playing at dice."

2.5 A TEST OF THE BINARY PHOTON: QUESTIONING THE RELATIVITY OF SPACE AND TIME

I have recently put the model of the binary photon to a test by describing and explaining the observed magnitude of the gravitational deflection of starlight—the *experimentum crucis* in favor of the general theory of relativity, in terms of the binary photon (Wayne 2012b,d).

By assuming that the gravity was not a Newtonian force that influenced massive objects directly, but that mass influenced the movement of mathematical point-like objects by warping an interdependent space–time through which they moved, Einstein (1916, 1920) predicted that starlight would be bent by the sun twice as much as was predicted by Johann von Soldner using the Newtonian model that gravity is a force that interacts with massive particles and that light itself was a particle with translational motion only (Jaki 1978).

Following the horrors of World War I, there was a favorable eclipse that allowed the deflection of starlight to be measured in the heavens (Figure 2.15). Dyson et al. (1920) found that "the results of the expeditions to Sobral and Principe can leave little doubt that a deflection of light takes place in the neighbourhood of the sun and that is of the amount demanded by EINSTEIN'S generalized theory of relativity." Following the observation of the signs in the heavens, Einstein became an instant celebrity. According to Subramanya Chandrasekhar (1983), Rutherford told him on May 29, 1919,

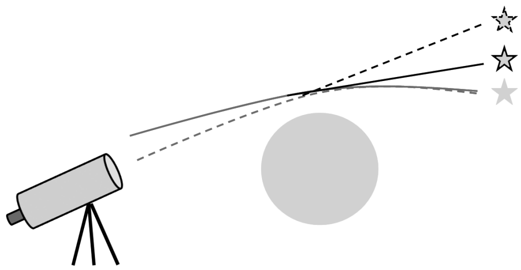

FIGURE 2.15 The deflection of starlight. As a result of the gravitational attraction of the sun, starlight composed of photons is deflected (dashed line) as it passes close to the sun. The star is assumed to exist in a direction parallel to the telescope axis. As a result of gravity, the source of the starlight (star without outline) appears to be displaced away from the sun (star with dashed outline). The observed *double* deflection is predicted equally well by (1) the general theory of relativity and (2) the binary photon theory. If the binary photon did not have rotational motion, the translational energy would be twice as large, and the starlight would be bent half as much (solid line). Since the starlight would be deflected half as much, the star would appear to be closer to the sun (star with solid outline).

> The war had just ended, and the complacency of the Victorian and Edwardian times had been shattered. The people felt that all their values and all their ideals had lost their bearings. Now, suddenly, they learnt that an astronomical prediction by a German scientist had been confirmed…by British astronomers. Astronomy had always appealed to public imagination; and an astronomical discovery, transcending worldly strife, struck a responsive chord. The meeting of the Royal Society, at which the results of the British expeditions were reported, was headlined in all the British papers: and the typhoon of publicity crossed the Atlantic. From that point on, the American press played Einstein to the maximum.

The *New York Times* (1919) reported that "if those English scientists are right in feeling that the theory is strongly supported we may be forced to conclude after all that our world is in just a topsy-turvy condition, and that we must learn the theory of relativity to understand it." Unfortunately, they also reported that "As all common folk are suavely informed by the President of the Royal Society that Dr. Einstein's deductions from the behavior of light observed during an eclipse cannot be put in language comprehensible to them, they are under no obligation to worry their heads, already tired by contemplation of so many other hard problems…."

How did Einstein the iconoclast that overturned Newton become an icon himself and *Time* magazine's *Person of the Century* (Golden 1999)? According to Pais (1994), in the wake of the horrors of World War I, Einstein "carried a message of a new world order in the universe"; and Einstein knew how to use language. Everyone knows what *space* and *warp* mean, yet hardly anyone understands what *warped space* is. Einstein himself said to a Dutch newspaper in 1921, "It is the mystery of the non-understanding that appeals to them…."

The general theory of relativity that posited that a relative and interdependent space–time directed the movement of a mathematical point like light quantum became accepted by the scientific community. In appreciation, Einstein (1923) won the Nobel Prize in Physics for 1921 "for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect" and gave his lecture on the fundamental ideas and the problems of the theory of relativity.

Is it possible that space is Euclidean and time is Newtonian and that the hidden properties revealed in the binary photon could explain the double deflection? Since the binary photon has angular momentum and radial extension, it must have rotational motion, which means that it must have rotational energy. If the binary photon had infinite translational energy, it would not be deflected by the sun, and if it had vanishing translational energy, it would fall into the sun. But, if the total energy of a binary photon ($E = h\nu$) is equipartitioned between the translational energy and the rotational energy, then the binary photon would have one-half of the expected translational energy. Consequently, the deflection of starlight would be twice a great as that which von Soldner predicted for a particle that has translational energy only (Wayne 2012b). The deflection of starlight composed of binary photons would also be equal to that predicted by Einstein (1916, 1920).

That is, the binary photon model, which assumes that the binary photon rotates as it translates through absolute space and time, gives the same prediction as Einstein's general theory of relativity. This means that the interpretation of the *experimentum crucis* that gave support for the relative and interdependent nature of space–time proffered by the general theory of relativity depends on the model of the photon. If the photon is a mathematical point whose energy cannot be partitioned into translational and rotational energy, then space and time must be relative and interdependent. However, if the photon is a binary compound with extension and its total energy is equipartitioned between its translational energy and its rotational energy, then space must be Euclidean and time must be Newtonian.

In the same paper in which I offered this interpretation of the deflection of starlight, I also offered a quantitatively accurate interpretation of the gravitational red shift. According to the general theory of relativity, the warping of space–time results in a reddening of the photons emitted by a star. According to the binary photon theory, the reddening results because the binary photon loses energy as it does work against the gravitational binding energy of a star. If the star is so massive, the reddening will be so extreme that the massive star would appear black in Euclidean space and Newtonian time (Wayne 2012b). According to the theory of general relativity, the atomic clocks of the global positioning system that emit photons of a given frequency must be adjusted to take into consideration the warping of space–time by the earth. According to the binary photon theory, the decrease in the frequency or *clock ticks* of the binary photons moving away from the earth and the increase in the frequency or *clock ticks* of the binary photons moving toward the earth result from the loss or gain in the energy of the binary photon due to the work done as it propagates against or along the gradient in gravitational binding energy (Wayne 2012b). The other successes of Einstein's theories of relativity are also understandable and explainable in terms of Euclidean space and Newtonian time.

According to Einstein (1923), the speed of light is a fundamental universal constant that relates relative space to an interdependent relative time and "to harmonize the relativity principle with the light principle, the assumption that an absolute time (agreeing for all inertial frames) exists, had to be abandoned." That is, the speed of light is a universal absolute that relegates space and time to relative geometrical quantities. The following equation expresses the relationship between absolute and relative quantities:

$$ds^2 = dx^2 + dy^2 + dz^2 - c^2dt^2 \tag{2.41}$$

where ds is a line element or world line in a Minkowski four-dimensional space–time. According to the theory of relativity, the square of the line element (ds^2) and the square of the speed of light (c^2) are constant for all observers, while the square of the distance in space ($dx^2 + dy^2 + dz^2$) and the square of the duration of time (dt^2) are relative quantities that depend on the velocity of the observer or the mass of an object—both of which warp space–time.

I asked myself if there could there be a heretofore hidden property of light itself that is relative when it moves through absolute space and time. Could Einstein have discounted such a property of light when he concentrated on its speed? The answer is, yes! The spatial extension of the binary photon allows one to see the fundamental nature of the wave-like properties of the binary photon that are subject to the Doppler effect expanded to the second order. The Doppler effect was discovered by Gregor Mendel's physics teacher, Christian Doppler (Baksalary and Styan 2009; Wayne 2013a) and I expanded it to second order.

Doppler (1842) guessed that the color of binary stars might be caused by their movement toward or away from an observer (Andrade 1959; Hujer 1963; Gill 1965; Toman 1984; Schuster 2005). Following the introduction of the rapidly moving steam locomotive, Christophorus Buijs Ballot (1845) tested Doppler's wave theory acoustically by placing musicians on a railroad train that traveled 40 mph past musically trained observers. The stationary observers perceived the notes played by the horn players to be a half-note sharper when the train approached and a half-note flatter when the train receded. Three years later, John Scott Russell (1848) noticed that when he was on a moving train, the pitch of the whistle of a stationary train was higher when the train moved toward it and lower when the train moved away. Further support for the Doppler effect came when Hermann Vogel (1876) quantified the increase and decrease in the pitch of a train whistle as the train approached or receded by matching the tone on a violin.

Following the rise of chemical spectroscopy (Roscoe 1869; Kirchhoff and Bunsen 1860), Ernst Mach (1860, 1873) and Hippolyte Fizeau (1870) proposed that the radial velocity of objects could be ascertained by observing the Doppler shift in the spectral lines that identified each chemical. The value of the Doppler effect on determining the velocity of objects was confirmed in the heavens (Huggins 1868; Slipher 1913) and in the laboratory (Bélopolsky 1901; Stark 1906; Galitzin and Wilip 1907). The cited acoustic and optical phenomena demonstrated the first-order Doppler effect. I have derived the Doppler effect expanded to the second order by starting with Maxwell's second-order wave equations (Wayne 2010b).

Einstein tried to reformulate Maxwell's wave equation so that it would take into consideration two inertial frames moving relative to each other but was unsuccessful (Wertheimer 1959). Consequently, he concluded that Maxwell's wave equation, as it was written with its single explicit velocity (c), was a fundamental law of physics valid in all inertial frames and that the speed of light was invariant. I have reformulated Maxwell's wave equation so that it takes into consideration the changes in the spatial and temporal characteristics of electromagnetic waves observed when there is relative motion between the inertial frame that includes the source and the inertial frame that includes the observer. My reformulation of Maxwell's wave equation is based on the primacy of the Doppler effect expanded to the second order, which is experienced by all waves (Wayne 2010b). Since, for any solution to the second-order wave equation in the form of $\Psi = \Psi_o e^{2\pi i\left(\frac{1}{\lambda}z - \nu t\right)}$, $\left(\frac{1}{\lambda}\right)$ and (z) as well as (ν) and (t) are complementary pairs $\left(\frac{r}{\lambda} \text{ and } \nu t\right)$, it is only a matter of taste which members of the pairs $\left(\frac{r}{\lambda}, \nu\right)$ or (z, t) one assumes to depend on the relative velocity of the source and the observer, and which members of the pairs one assumes to be invariant. Einstein chose z and t to be velocity-dependent and $\frac{1}{\lambda}$ and ν to be invariant in all inertial frames, and I chose $\frac{1}{\lambda}$ and ν to be velocity-dependent and z and t to be invariant in all inertial frames. The Doppler-based relativistic wave equation is given below in two equivalent forms—the first emphasizing symmetry and the second, which is Equation 2.42 multiplied by $\frac{c\sqrt{c - v\cos\theta}}{c\sqrt{c - v\cos\theta}} = 1$, emphasizing the similarity with the Lorentz transformation:

$$\frac{\partial^2\Psi}{\partial t^2} = cc'\frac{\sqrt{c - v\cos\theta}}{\sqrt{c + v\cos\theta}}\nabla^2\Psi \tag{2.42}$$

$$\frac{\partial^2\Psi}{\partial t^2} = cc'\frac{1 - \frac{v}{c}\cos\theta}{\sqrt{1 - \frac{v^2\cos^2\theta}{c^2}}}\nabla^2\Psi \tag{2.43}$$

The magnitude of the relative velocity of the source and the observer is given by v; θ is the angle subtending the velocity vector originating at the source and the wave vector originating at the source and pointing toward the observer; c is the speed of light through the vacuum and is equal to $\frac{1}{\sqrt{\varepsilon_o\mu_o}}$; and c' is the product of the frequency (ν_{source}) of the source in its inertial frame and the wavelength ($\lambda_{observer}$) observed in any inertial frame. When the source and the observer are receding from each other, $\theta = \pi$ radians, and when the source and the observer are approaching each other, $\theta = 0$ radians. The following equation is a general plane wave solution to the second-order relativistic wave equation given above:

$$\Psi = \Psi_o e^{2\pi i\left(\frac{z}{\lambda_{observer}} - \nu_{source}\frac{1 - \frac{v}{c}\cos\theta}{\sqrt{1 - \frac{v^2\cos^2\theta}{c^2}}}t\right)} \tag{2.44}$$

Solving the relativistic wave equation for the speed of the wave c results in the following relativistic dispersion relation:

$$c = \lambda_{observer}\nu_{source}\frac{1 + \frac{v}{c}\cos\theta}{\sqrt{1 - \frac{v^2\cos^2\theta}{c^2}}} = 2.99\times10^8 \text{ m/s} \tag{2.45}$$

indicating that the speed of light (c) is equal to 2.99×10^8 m/s and is independent of the velocity of the observer. When v vanishes, the source and the observer are in the same inertial frame, and the relativistic dispersion relation reduces to the standard dispersion relation $c = \lambda_{source}\nu_{source}$. After replacing ν_{source} with $\frac{c}{\lambda_{source}}$, Equation 2.45 transforms into a simple, perspicuous, and lucid relativistic equation that describes the new relativistic Doppler effect:

$$\lambda_{observer} = \lambda_{source}\frac{1 - \frac{v}{c}\cos\theta}{\sqrt{1 - \frac{v^2\cos^2\theta}{c^2}}} \tag{2.46}$$

and the effect of relative velocity on the wavelength of the observed light.

The Doppler effect expanded to second order differs from the first-order Doppler effect in that the denominator in the first-order Doppler effect is unity. Consequently, as a result of the first-order Doppler effect, at any relative velocity, the *average* wavelength of light observed by or colliding with an observer or object from the front and the back is unchanged and predicted to be (Page 1918)

$$\lambda_{observer} = \lambda_{source}\frac{1}{2}\left[\left(1 - \frac{v}{c}\right) + \left(1 + \frac{v}{c}\right)\right] = \lambda_{source}. \tag{2.47}$$

By contrast, when the Doppler effect is expanded to the second order, at any relative velocity, the *average* wavelength of light observed by or colliding with an observer or object from the front and the back will change and will be given by:

$$\lambda_{\text{observer}} = \lambda_{\text{source}} \frac{1}{2}\left[\left(\frac{1-\frac{v}{c}}{\sqrt{1-\frac{v^2\cos^2\theta}{c^2}}}\right)+\left(\frac{1+\frac{v}{c}}{\sqrt{1-\frac{v^2\cos^2\theta}{c^2}}}\right)\right] = \frac{\lambda_{\text{source}}}{\sqrt{1-\frac{v^2\cos^2\theta}{c^2}}} \tag{2.48}$$

The equation, which describes the new relativistic Doppler effect, differs from Einstein's relativistic Doppler effect equation by having a cosine term in both the numerator and the denominator. The cosine term describes the dependence of the first-order and second-order velocity-dependent spatial properties of electromagnetic waves on the component of the velocity relative to the propagation vector. Unlike Einstein's relativistic Doppler effect, where the term in the denominator describes the relativity of time independent of the propagation vector, the new relativistic Doppler effect shown here does not predict a transverse Doppler effect when $\theta = \frac{\pi}{2}$ since at this angle, $\cos\theta = 0$. The Doppler effect expanded to the second order will cause a velocity-dependent change in the observed length (L_{observer}) of the binary photon according to the following equation:

$$L_{\text{observer}} = \lambda_{\text{source}} \frac{1-\frac{v}{c}\cos\theta}{\sqrt{1-\frac{v^2\cos^2\theta}{c^2}}} \tag{2.49}$$

and a velocity-dependent change in its observed cross-sectional area (A_{observer}) according to the following equation:

$$A_{\text{observer}} = \pi r^2 = \pi \frac{\lambda^2_{\text{source}}}{(2\pi)^2}\left[\frac{1-\frac{v}{c}\cos\theta}{\sqrt{1-\frac{v^2\cos^2\theta}{c^2}}}\right]^2 = \frac{\lambda^2_{\text{source}}}{4\pi}\left[\frac{1-\frac{v}{c}\cos\theta}{\sqrt{1-\frac{v^2\cos^2\theta}{c^2}}}\right]^2 \tag{2.50}$$

I assume that the velocity-induced change in the cross-sectional area of the binary photon is a result of the equipartition of energy between the longitudinal motion and the rotational motion. Indeed, the fact that the entropy (S) of a photon is $2.60k$, where k is Boltzmann's constant, indicates that a photon has approximately 36 microstates (Ω) among which to share the entropy (Wayne 2015):

$$S = k \ln \Omega \tag{2.51}$$

Red-shifted and blue-shifted binary photons are shown in Figure 2.16. Curiously, even though the Doppler effect is

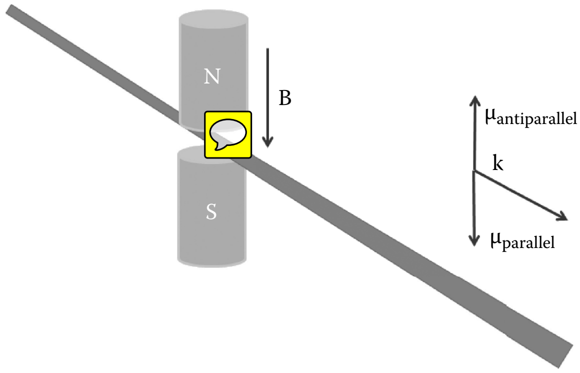

FIGURE 2.16 Red-shifted and blue-shifted binary photons. The Doppler effect will cause a velocity-dependent change in the length and cross-sectional area of the oscillating binary photon.

readily perceived when there is relative motion, whether one is looking at the water waves produced by a swimming swan, the water waves striking a cattail, the sound waves produced by the siren on a fire truck, or the light coming from a distant galaxy, standard theories rarely, if ever, include the Doppler effect as a primary consideration in the study and description of relative motion. The analyses done by my colleagues and me (Wayne 2010a,b, 2012a, 2013c, 2015; Maers and Wayne 2011; Maers et al. 2013) are unique in that we incorporate the relativistic Doppler effect *ab initio*. When expanded to the second order, the inclusion of the Doppler effect makes it possible to unify many aspects of mechanics, electrodynamics, and optics that are usually treated separately. Indeed, the Doppler effect expanded to the second order combined with absolute time also provides alternative derivations of results familiar from the special theory of relativity describing the relativity of simultaneity and why charged particles cannot exceed the vacuum speed of light. It also describes the optics of moving bodies, the mass equivalent of energy, and allows the combination of Newton's second law with the second law of thermodynamics to produce a fundamental, relativistic, and irreversible law of motion.

Einstein lived at a time when fast moving coal-powered trains and telegraphic communication made time seem as if it were relative (Galison 2003). Imagine someone living at that time who was 1000 miles away telling you that their train or a telegram was going to arrive at 12 o'clock noon. Which 12 o'clock noon, the noon of the person telling you or the noon of the person waiting for the train or the telegram? The confusion led to the creation of standard time (Blaise 2000). Before the creation of standard time in 1884, there was local time or solar time where each community reckoned 12 o'clock noon to be the time that the sun was highest in the sky at that location.

In his book *Relativity: The Special and the General Theory*, Einstein (1920) used a train analogy developed by David Comstock (1910) to describe the foundations of the special theory of relativity to a general audience in a non-mathematical manner.

Einstein (1920) demonstrated that time is relative by comparing the observations of a person on "a very long train

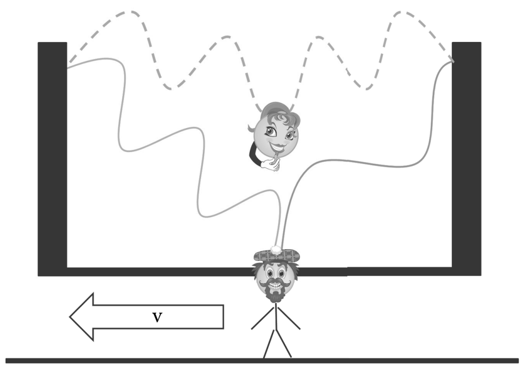

FIGURE 2.17 The observer in the railroad car midway between the lights sees two identical lights come on simultaneously, while the observer on the platform, midway between the two lights and moving backward relative to the railroad car, sees the light from the back come on before the light from the front.

travelling along the rails with the constant velocity *v*" with the observations made by a person on a "railway embankment." He asked the reader to picture an observer in a railroad car midway between light sources at the back of the railroad car and at the front of the railroad car (Figure 2.17). This observer would see the lights come on simultaneously. By contrast, an observer standing on the railway embankment, who is moving backward at velocity *v* relative to the train, would see the light at the back of the railroad car come on before the light at the front of the railroad car comes on. Since there was only one simultaneous event observed by the person on the train, but two nonsimultaneous events observed by the person on the embankment, Einstein concluded that time was relative and the time reckoned depended on the relative velocity of the observer.

Working at a time when transformations between local times and standard time were being made by engineers and telegraph operators, Einstein was immersed in the relativity of time. Combined with the fact that he considered light to be a mathematical point where wavelength and frequency were just numbers that represented momentum and energy, Einstein considered the relativity of time to be a more reasonable explanation than the relativity of wavelength and frequency (i.e., color) due to the Doppler effect. By contrast, I am immersed in a time of Doppler radar, Doppler weather, Doppler ultrasound, and Doppler MRI (Doviak and Zrnić 1993; Maulik 1997; Baksalary and Styan 2009), and as a child of the 1960s, how could I not appreciate the train metaphor in terms of the Doppler effect and the relativity of color?

While there is a lack of clarity as to whether color is described by wavelength or by frequency (Johnsen 2012), the color of light can be described equally well in terms of wavelength and frequency (Wayne 2014c). According to the Doppler theory (Wayne 2010b), if the person in the railroad car midway between the lights at the back and front of the railway car sees the lights come on simultaneously, he or she would see them to be the same color. By contrast the person on the embankment would see the light at the back of the train to be bluer and the light at the front of the train to be redder as a result of the Doppler effect expanded to the second order and the relative motion between the train and the person on the railway embankment. While the velocities of the blue-shifted and red-shifted light are the same and equal to *c*, the speed of light in free space, the amplitude, energy, or probability of finding a photon (Born 1954; Bloch 1976) described by the blue-shifted wave arrives at the observer before the amplitude, energy, or probability of seeing a photon described by the red-shifted wave arrives at the observer. Consequently, the person on the platform would not observe the two lights coming on simultaneously, but because of the difference in the wavelengths that results from the Doppler effect, the person on the railway embankment would observe the blue-shifted light from the back before observing the red-shifted light from the front.

The Doppler effect experienced by the binary photon can also be used to describe and explain the electrodynamics of moving bodies and why particles with a charge and/or a magnetic moment cannot go faster than the speed of light (Wayne 2010a; Figure 2.18). When an electron is accelerated through an electric field in a cavity, it moves through a photon gas. According to Planck's blackbody radiation law, the greater the temperature of a cavity, the greater the number of photons in the cavity and the shorter their wavelength. This means that at any temperature greater than absolute zero, which, according

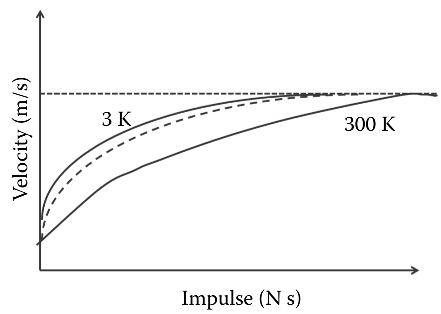

FIGURE 2.18 Particles cannot exceed the speed of light. The reason why a particle with a charge and/or a magnetic moment cannot exceed the speed of light is explained by the special theory of relativity by saying that the duration of time that the electron experiences the accelerating field gets shorter and shorter as the particle gets faster and faster, and consequently, it accelerates less and less. As the particle approaches the speed of light, the duration of time is so short that the particle can no longer accelerate. According to the special theory of relativity, the particle is only moving through a relative and interdependent space–time. The Doppler theory also explains why particles with a charge and/or a magnetic moment, the only kind of particles that can interact with binary photons, the carrier of the electromagnetic force, cannot exceed the speed of light. Special relativity makes no predictions about the effect of temperature on the velocity–impulse relation, while the Doppler theory predicts that as the temperature increases, the impulse needed to accelerate a particle to a given velocity will be greater as a result of the increased velocity-dependent optomechanical counterforce caused by the binary photons on the charged particle.

to the third law of thermodynamics developed by Walther Nernst, is unattainable, there will be photons. This means that there will be binary photons in any space through which a particle with charge and/or magnetic moment moves.

If a particle is moving through a photon gas, then the binary photons that scatter from the front of the moving particle will be blue-shifted as a result of the Doppler effect expanded to the second order, and the binary photons that scatter from the back of the moving particle will be red-shifted (Figure 2.19). The binary photons that collide with the back of the moving particle can also be considered to be red-shifted as a result of the Compton effect, and the binary photons that collide with the front of the moving particle can also be considered to be blue-shifted as a result of the inverse Compton or Sunyaev-Zel'dovich effect (Rybicki and Lightman 1979; Shu 1982).

Since the energy and linear momentum of binary photons are inversely proportional to their wavelength, the blue-shifted binary photons that collide with or scatter from the front of a moving particle will push the particle backward more than the red-shifted binary photons that collide with or scatter from the back of the moving particle will push the particle forwards. The faster the particle moves, the greater the difference is between the wavelengths of the binary photons hitting the front and back of the moving particle, and the greater the optomechanical counterforce is provided by the binary photons through which the particle moves. As the electron approaches the speed of light, the counterforce approaches the accelerating force. Since the acceleration of the electron is proportional to the difference between the accelerating force and the counterforce, when the counterforce equals the accelerating force, acceleration is no longer possible. This means light itself prevents a particle with charge and/or magnetic moment from moving faster than the speed of light.

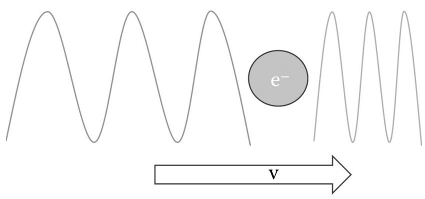

FIGURE 2.19 According to the Doppler theory, at any temperature greater than absolute zero, the particle is moving through a photon gas described by Planck's blackbody radiation law. As the particle moves through the photon gas, it experiences the photons through which it moves as being Doppler shifted. The binary photons that strike the leading side of the particle are blue-shifted by the Doppler effect, and the binary photons that strike the trailing side of the particle are red-shifted. The greater the particle velocity, the greater the difference between the blue-shifted and red-shifted binary photons. Since the linear momentum of the binary photons is inversely proportional to their wavelength, the binary photons through which the particles move exert an optomechanical counterforce on the moving particle. In this way, light itself prevents particles with a charge and/or a magnetic moment from exceeding the speed of light. Only particles with a charge and/or a magnetic moment are able to interact with the binary photons, the carriers of the electromagnetic force.

Friction in physics is considered to be fundamentally negligible and unimportant (Einstein and Infeld 1938). However, a biophysical plant biologist knows that a frictional counterforce is experienced by anything that moves, including a substrate diffusing toward an enzyme (Wayne 2009b), the thylakoids moving through the stroma during chloroplast biogenesis (Paolillo Jr. and Reighard 1967), nuclear-encoded proteins passing through the chloroplast envelope (Jarvis and López-Juez 2013), proteins trafficking through plastid stromules (Hanson and Sattarzadeh 2013), chloroplasts moving through the cell (Kadota et al. 2009; Wada 2013), and leaves tracking the movement of the sun (Koller 2011). By extrapolation, I have found that at any temperature above absolute zero, friction is inevitable and that the binary photons have the properties necessary to provide the optomechanical counterforce that prevents particles, with a charge and/or magnetic moment that makes them capable of interacting with photons, from exceeding the speed of light.

According to the optomechanical model of how binary photons limit the speed of a moving particle to that of light, the greater the temperature of the space through which the particle moves, the greater the number of binary photons and the greater the optomechanical counterforce or the resistance to acceleration. Consequently, the optomechanical counterforce hypothesis is testable since the counterforce exerted on the moving particle increases with temperature. If the speed in which a particle is accelerated by an impulse *is not* temperature dependent, then the special theory of relativity gives a better explanation of the limiting speed of particles. If the speed in which a particle is accelerated by an impulse *is* temperature dependent, the theory of the optomechanical counterforce provided by Doppler-shifted binary photons gives a better explanation of the limiting speed of particles. I look forward to someone measuring the impulse–velocity relationship at 3 and 300 K in a linear accelerator. According to the optomechanical counterforce theory, the impulse needed to accelerate a particle to a given velocity should be 10,000 times greater at 300 K than at 3 K (Wayne 2010a).

When we look at the development of the photosynthetic system (Majeran et al. 2010) and the *adaptive walk* taken in the evolutionary history of photosynthetic plants (Niklas 1997), there seems to be an undeniable arrow of time. Yet, according to the standard model of physics, time is an illusion because the fundamental equations of physics do not have an arrow of time. According to Brian Greene (2004), "Even though experience reveals over and over again that there is an arrow of how events unfold in time, this arrow seems not to be found in the fundamental laws of physics." However, the reversibility of time *is* the foundational assumption and *only* equations that are quadratic in time (t^2) are allowed to be called fundamental. This is why the second law of thermodynamics, which according to me foundationally describes and explains the observed unidirectional arrow of time, is not considered to be a fundamental law of physics.

By taking into consideration the optomechanical counterforce produced by Doppler-shifted binary photons, I have been able to combine Newton's second law of motion with the second law of thermodynamics to produce a fundamental, relativistic, and irreversible law of motion (Wayne 2012a). It states that processes are irreversible because Doppler-shifted binary photons that collide with any moving object radiate away at the speed of light. These binary photons cannot be rounded up to reverse the natural process.

2.6 THE REAL WORLD: MATHEMATICAL OR MORE?

Is it possible to come up with laws of physics that coincide with the visual world? In his Nobel lecture, Heisenberg (1933) stated that "The impossibility of harmonizing the Maxwellian theory with the pronouncedly visual concepts expressed in the hypothesis of light quanta subsequently compelled research workers to the conclusion that radiation phenomena can only be understood by largely renouncing their immediate visualization." One could no longer ask where is a given photon in space and time? Because, according to Walter Heitler (1944) "there are no indication that, for instance, the idea of the 'position of a light quantum' (or the 'probability for the position') has any simple physical meaning." More recently, David Griffiths (2005) wrote,

> The particle wasn't really anywhere. It was the act of measurement that forced the particle to 'take a stand' (though how and why it decided on the point C we dare not ask). Jordan said it most starkly, 'Observations not only disturb what is to be measured, they produce it…. We compel (the particle) to assume a definite position.' This view (the so-called Copenhagen interpretation), is associated with Bohr and his followers. Among physicists it has always been the most widely accepted position.

According to Armstrong (1983), the photon is not a physical unit with any form of localization but more like coefficients in a Fourier series until it is commanded into existence.

Mathematics seems to have trumped other forms of knowledge about the natural world. James Jeans (1945) wrote that "the history of theoretical physics is a record of the clothing of mathematical formulae which were right, or very nearly right, with physical interpretations which were often very badly wrong." In *The Mysterious Universe*, Jeans (1934) wrote,

> Lapsing back again into the crudely anthropomorphic language we have already used, we may say that we have already considered with disfavour the possibility of the universe having been planned by a biologist or an engineer; from the intrinsic evidence of his creation, the Great Architect of the Universe now begins to appear as a pure mathematician.

I think that the current mathematical models in physics that consider all particles fundamentally as mathematical points, matter as being fundamentally massless, friction to be a fiction, and space and time to be fundamentally an illusion are too simplistic in their assumptions, and, because of this, they may be misleading when it comes to describing the real world. Consequently, I am endeavoring to create a realistic theory of the photon, which inevitably creates friction as a result of the Doppler effect expanded to the second order, where space and time are real-world quantities defined by common sense and only approximated by mathematical equations (Synge 1951, 1970). My point of view contrasts with the mathematical physicists who think that the mathematical equations are fundamentally real and anything less abstract is accidental and misleading (Tegmark 2007).

After reading Hermann Weyl's book *Space, Time and Matter*, Felix Bloch (1976) told Heisenberg "that space was simply the field of linear operations." Heisenberg replied, "Nonsense, space is blue and birds fly through it." Heisenberg was warning Bloch that "it was dangerous for a physicist to describe Nature in terms of idealized abstractions too far removed from the evidence of actual observation." Einstein also thought that idealized abstractions provided inadequate pictures of the world. When Max Born's wife Hedwig asked Einstein, "Do you believe that everything can be pictured in a scientific manner?" Einstein answered, "Yes, it is conceivable but it would be of no use. It would be an inadequate means of expression—like representing a Beethoven symphony in terms of curves of air pressure" (Born 1965).

Wholistic, intuitive, aural, and visual interpretations of reality contrast with the current orthodox interpretation of reality where reality is completely described mathematically by the foundational principles of uncertainty and relativity, and consequently, events do not really take place in a cause and effect manner over time in three-dimensional space. According to Bohr (1934), the commonsense yet illusional view of reality prevails because most people do not have experience with velocities that are comparable to the speed of light and with objects as small as atoms (Miller 1994). The binary photon allows for a physical and mathematical description of the real world, capable of visual imagery, and consistent with common sense and intuition, where time differs from space, friction is not a fiction, and all effects require a cause.

2.7 SUMMARY OF THE PROPERTIES OF A BINARY PHOTON

The importance of plants in transforming the energy of light to the requirements for life was recognized by Julius Robert Mayer (1845), the founder of the first law of thermodynamics (Tyndall 1915). Mayer wrote,

> Nature undertakes the task of storing up the light which streams earthward—of condensing the most volatile of all powers into a rigid form, and thus preserving it for our use. She has overspread the earth with organisms which while living take into them the solar light, and by the appropriation of its energy generate incessantly chemical forces. These organisms are plants. The vegetable world constitutes the reservoir in which the fugitive solar rays are deposited, and rendered ready for useful application. With this economical provision the existence of the human race is also inseparably connected. The reducing action exerted by solar light on both inorganic and organic substances is well known. This reduction takes place most copiously in full sunlight, less copiously in the

shade, being entirely absent in darkness, and even in candlelight. The reduction is a conversion of one form of energy into another—of mechanical effect into chemical tension.

Given the importance of light to plant life in terms of photosynthesis, photomorphogenesis (Wayne and Hepler 1984, 1985), and photomovement (Wayne et al. 1991), I became interested in the nature of the photon. The nature of the light quantum has been questioned ever since Einstein proposed it in 1905. On December 12, 1951, Einstein wrote to his friend Michele Besso: "All the fifty years of conscious brooding have brought me no closer to the answer to the question, 'What are light quanta?' Of course, today, every rascal thinks he knows the answer, but he is deluding himself" (see Klein 1970). The ideas on the nature of the photon that I present here are incomplete and still in progress. While they are the best I have to offer, some may be wrong. Arthur Schuster (1898), the person who first came up with the idea of antimatter, reminds us that as scientists, occasionally we should think about the unknown and perhaps even the unknowable. I hope my ideas developed from by background as a biophysical plant biologist have stimulated you to think about the photon. Here is a summary of my conclusions:

- The photon is not an elementary particle but a composite particle composed of two semiphotons and a boson composed of two fermions. The mass of the boson is not unique but depends on the frequency of the photon.
- The semiphotons are conjugate particles. One semiphoton has positive mass and the other has negative mass. The positive mass semiphoton is equivalent to a particle (matter), and the negative mass semiphoton is equivalent to an antiparticle (antimatter).
- A binary photon cannot occupy a single mathematical point and thus by necessity it must have extension.
- The gravitational force between the two conjugate particles provides the motive force that causes the negative mass semiphoton to chase the positive mass semiphoton unidirectionally in space and time. This is why light moves.
- As the carrier of the electromagnetic force, the binary photon must carry charge yet remain neutral. To remain electrically neutral, the semiphotons have opposite charges. The charges of the semiphotons confine the speed of the center of gravity of the binary photon to the speed of light.
- The two semiphotons rotate with opposite senses around the axis of propagation in a manner that gives the binary photon one unit of angular momentum and a magnetic moment. In so doing, the semiphotons generate a transverse linearly polarized electric field and electric dipole moment that is equivalent to Faraday's electric line of force. The rotation of the semiphotons also results in a three-dimensional and predominantly longitudinal magnetic field, equivalent to Faraday's magnetic line of force. The binary photon, with its electric dipole moment and orthogonal magnetic moment, is fit to be the gauge boson that carries the electromagnetic force.
- The internal structure of the binary photon, represented by the time-varying electric and magnetic fields, may provide the hidden variables or the variables that were hidden to the founders of quantum mechanics that call into question the fundamental nature of the uncertainty principle.
- The model of the binary photon has been tested in that it is able to predict the double deflection of starlight in Euclidean space and Newtonian time as well as the general theory of relativity does for a mathematical point-like photon in warped space–time.
- By postulating that the Doppler effect expanded to the second order is fundamental and that the wavelength and frequency of light are relative and space and time are absolute, the relativity of simultaneity as well as the reason why a particle with a charge and/or magnetic moment cannot exceed the speed of light can be described and explained in terms of the binary photon moving through Euclidean space and Newtonian time. Thus, the postulate of an interdependent and relative space–time may be superfluous, and the foundational value of the special and general theories of relativity may be called into question by the binary photon.
- The binary photon, with its time-varying electrical dipole and magnetic moments, is fit to initiate photochemical charge separation that leads to the photosynthetic fixation of carbon dioxide, the evolution of oxygen, and life as we know it.

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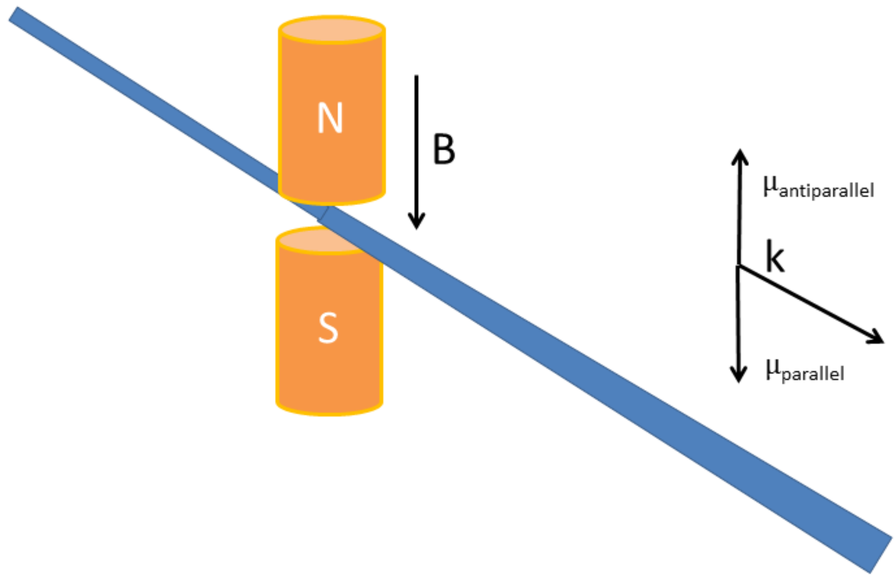
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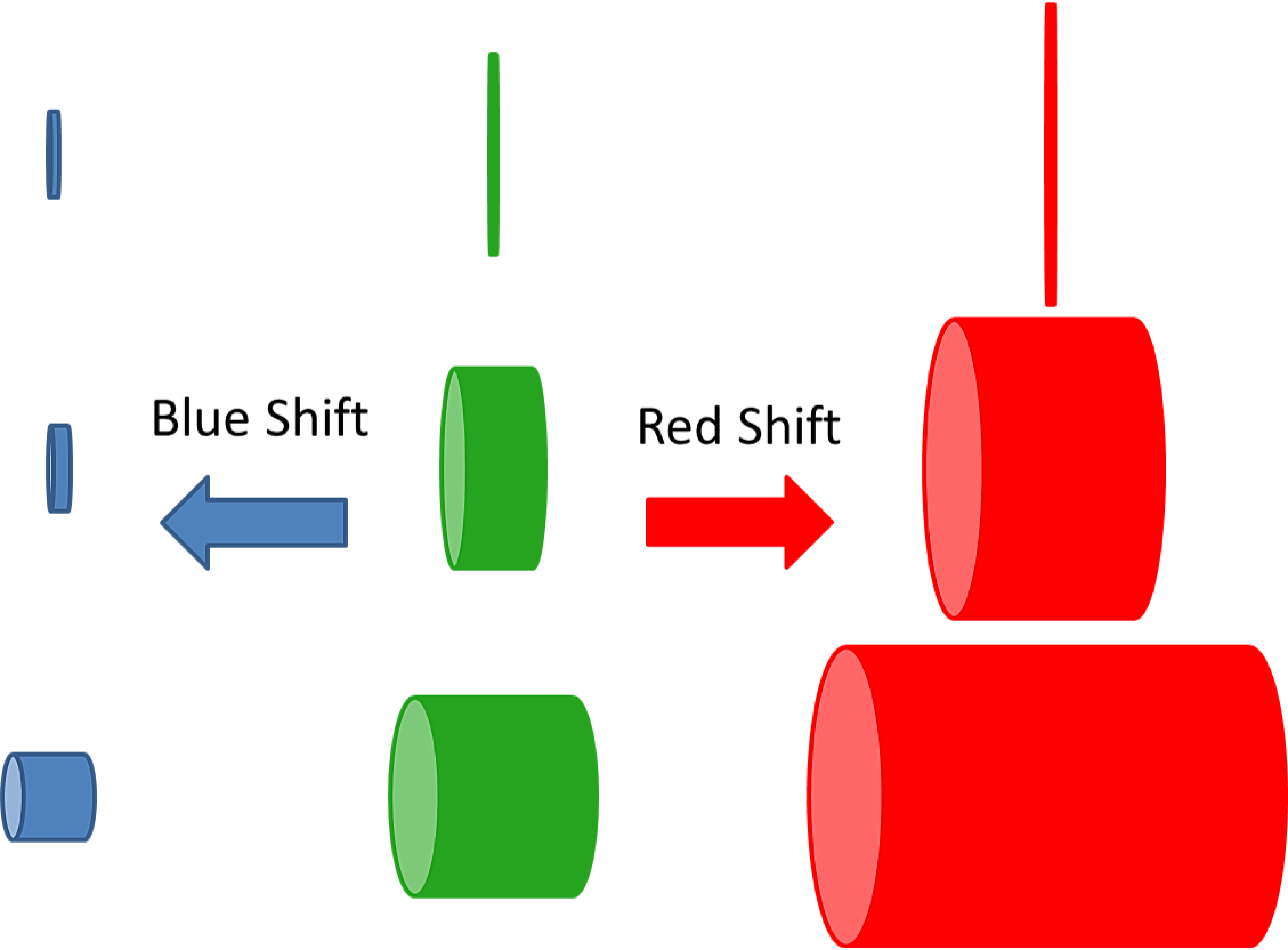
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