Chapter 3

The Visual Stimulus

NEED FOR A PHYSICAL DEFINITION OF THE STIMULUS

Samuel Johnson is reported to have said, "We all know what light is; but it is not easy to tell what it is" (Falk, Brill & Stork, 1986). Because light is the stimulus to which the eyes respond, it is incumbent on us to make an attempt to tell what it is.

We use our various senses to infer that there is a world outside our own bodies; one that is filled with objects that seem to have a physical reality. Most of us see desks, tables, people, animals, automobiles, and so forth — objects seemingly arranged in meaningful ways in an external world. Physical scientists, in addition, pay attention to molecules, photons, subatomic particles, magnetic flux, and so forth. Most of these physical entities are difficult or impossible to visualize and can be "seen" only in the same cognitive sense that a blind person might say "Yes, I see what you mean." Such physical concepts are sometimes made easier to understand when an attempt to visualize the concept is made. These concepts are also used to build models whose behavior matches our observations. We learn to diagram an atom as having a spherical nucleus surrounded by little whirling balls, although we are cautioned (if we are well taught) that this is only a representation, nothing more than a metaphorical visual crutch, crudely representative of mathematical relations that provide a more accurate description.

In casual, everyday activities we have come to rely on our observations by direct perception. These abilities probably evolved as a result of our adaptation to, and survival in, our external environment. If, say, magnetic fields carried significant information for us, we probably would have evolved with magneto-receptors. That we have not may be taken as evidence that there are other forms of physical disturbances available in the sea of energy within which we live that are more significant for our survival. We have developed specialized receptive equipment that is specifically tuned to what is most important. Although our perceptions work well for us much of the time, we should be prepared to understand that they are limited. In our understanding of color vision we must force ourselves to realize that, although our observations are of a special kind, they are limited and it is frequently necessary to use special devices to make indirect observations of our visual environment.

Survival on earth is not dependent on an accurate perception of the universe or, until very recently, even on what is happening on the other side of the mountain. We usually survive without being able to see microorganisms, although occasionally they are lethal. It must be emphasized that the perceptual powers that we do possess, utilizing our unaided perceptual capacities, are impressive indeed. We may suppose that, if we could see the microscopic world or react directly to static magnetic fields (as some birds apparently do), the capacity to do so would only have evolved at the expense of the significant and presumably more important perceptual powers that we possess instead.

Although we cannot directly perceive the world in a way that accords with its description in physical terms, there is no reason to deny the physical existence of ordinary objects, such as a blue book on the desk. You can, after all, confirm its existence in many ways: by feeling it, by lifting it to discern its heaviness, by blowing on its surface in order to sense the reflected wind, or by slapping it hard so as to hear the sound that this makes and to feel a sting in your fingers. You can hold the book to the light and note that it is impossible to see through it. You can try to bend it in order to gain an impression of its physical resistance. All of these events interact to confirm your perception, initially based on the remarkable act of vision at a distance, that there is indeed a book lying on your desk. Yet of all the properties that the book seems to possess, its color is something special because you are unable to confirm it by any of these other operations; only your eyes can tell you that the book appears blue.

As was pointed out in Chapter 1, it is obvious that we are not in direct contact with such remote objects whose forms we can recog-
nize and whose colors we can identify. We seek in this book to deal
with current conceptions of how such visual perception is possible.
We have seen that prescientific efforts to gain such understanding
led to concepts that were necessarily speculative, and usually untrue.
It is evident that we are not in mechanical contact with the visual
object that is perceived. Rather, light reflected from the object en-
ters our eyes, stimulates our retinas (strictly speaking, the retina is an
extension of the brain), and indirectly activates our brains. Some-
how, from this activity, we gain an appreciation of the presence of
the object and of its color.

It is tempting to fall into a trap, as the Greek philosophers and,
more recently, the Gestalt psychologists did, of defining the perceived
object as constituting a "stimulus for vision." To say that one per-
ceives a pen lying on the desk because the "pen" stimulates the eyes
is not to solve the problem of perception, but merely to state that
perception occurs. What we require instead is a sufficiently detailed
description of the object that is independent of the object's subject-
ive appearance. Anything less inevitably begs the question.

Ideally, physical descriptions should be free of the raw power of
people's sensory processes. This power is so important in everyday
life and so vital to certain fields of endeavor, such as art and litera-
ture, that it may be difficult to accept the view that, for the clear
understanding of this power itself, a different (and more difficult)
description of the stimulus is required. The physical environment so
conceived has a nature and presence that does not depend on whether
anyone is around to perceive it. The tree falling in the forest pro-
duces a physical sound whether or not anyone is there to hear it. A
description of the pen on a desk should be possible using concepts
that do not presume that the pen necessarily will be perceived by
anyone, but which does assume that it has a physical existence that
can be given an independent description.

PRIMARY STIMULUS FOR VISION

If one receives a blow to the head, it is not uncommon to have a visual
sensation. We frequently say that we "see stars." It is also possible to
have a visual experience by pressing firmly on the eye through closed
eyelids. It has been demonstrated that a visual experience can be achieved
by passing a mild electric current across the eye. (While the
reader may wish to press on the eye, he or she is definitely cautioned
not to pass an electric current across the eye.) While the eye will
respond to such mechanical or electrical stimulation, the visual recep-
tors clearly have not been designed for these purposes. The receptors
are designed to receive and process electromagnetic energy from a
very narrow part of the electromagnetic spectrum that encompasses
wavelengths between about 380 and 750 nm. This part of the spec-
trum is called light, and light is the primary stimulus for vision.

LIGHT

In the 1792 edition of the *Encyclopedia Britannica* it is stated:\n"It is obvious . . . that whatever side we take concerning the nature of
light, many, indeed almost all the circumstances concerning it, are
incomprehensible and beyond the reach of human understanding."

One hundred seventy-six years later, in the September 1968 special
edition of *Scientific American* on "Light," Gerald Feinberg wrote:\n
\[
\text{At present the photon theory gives us an accurate description of all we}
\text{know about light. The notion that light is fundamentally just another}
\text{kind of matter is likely to persist in any future theory. That idea is the}
\text{distinctive contribution of 20th-century physicists to the understand-
\text{ing of light, and it is one of which we can well be proud.}
\]

Photons

The quotations above provide us with a starting point for our dis-
cussion of light, which is the primary stimulus for color vision. We see
from these quotes that the early view that light could never be under-
stood has given way to a modern conceptualization that light cons-
ists of particles, called photons.

A photon is an indivisible unit of radiant energy. The amount of
energy associated with a photon of wavelength \( \lambda \) is

\[
E = \frac{hc}{\lambda}
\]

where \( E \) = energy (erg), \( h = 6.626 \times 10^{-34} \) J \cdot s \ (Planck's Constant), \( c = 2.997 \times 10^8 \) m \cdot s\(^{-1}\) (velocity of light), and \( \lambda \) = wavelength. Put another
way, a photon is the smallest amount of energy associated with \( \lambda \);
thus, short wavelength photons "pack more punch" than long wave-
length ones because short wavelength photons are of a higher fre-
quency than long wavelength ones.

The brighter a light is, the more photons are contained in it.
Because photons are discrete packets of energy it is not possible to
absorb a fraction of a photon. When a photon is emitted from a source
it immediately moves at the speed of light. It is a mistake to assume
that a photon can occupy a specific position. Light has a zero rest
mass: despite this, photons are never at rest, and in their actual state of motion they possess energy and momentum. It is thus to be expected that a beam of light should be capable of exerting pressure on a physical object, and it is reassuring to find that this actually happens. But the momentum possessed by each photon is exceedingly small, despite its velocity (which in a vacuum is the highest attainable in nature). For most purposes, including vision, the pressure that light exerts is negligible and has nothing to do with the extent of its stimulating capacity.

During the life of a photon, the energy it possesses is maintained at an exact value, and to a first approximation it moves in a straight line. In a vacuum, it would continue to do so forever. As discussed below, other fates are possible for photons that move within environments containing other particles of matter with which photons may interact. Photons that emerged from distant stars, hundreds or even millions of years ago, reach our eyes unchanged. It is conceptually important, and awe inspiring, to realize that these particles of light are in no sense “tired” and they do not lose the capacity to stimulate the eye during their long journey to earth. On the other hand, when we look at a mountain that is 50 miles away, light reflected from that source takes 0.00027 s to reach our eyes. We will see in Chapter 9 that the physiological latencies involved in visual information processing are orders of magnitude greater than this, meaning that even if light did travel with infinite velocity — as the ancients believed — there would be very few situations where one could tell the difference.

Because light within a homogeneous medium moves in straight lines, inferences can be made about the location of its origin. We will see below something of how the eye does this, by mapping all light that originates from a given point in space upon a restricted region of the retina. The path of light corresponds to what is called, in geometric optics, a ray.

A typical environment containing a source of illumination is packed solid with such light rays because such an environment will also contain numerous reflecting surfaces. (If one were in an environment where all surfaces were perfectly absorbing and there were no visible particles in the air, then one would see the light source and nothing else.) Given a reasonable sampling time, an arbitrary point in a normal environment would have rays passing through it in all possible directions. If the amounts of light per unit time defining these rays were all equal, there would obviously be no basis for pattern vision: such a situation exists in a perfect Ganzfeld and is approximated in an Arctic whiteout, being inundated by a superdense fog, or in the center of an integrating sphere. In the real world sources of light are nonuniformly distributed; their output varies with direction and surfaces vary in their reflectivity. Consequently, if one were able to sample a given point in the environment one would find that the rate of photon flow in certain directions would exceed that in others. At each location in the environment where an eye might be, the proximal basis for visual perception lies in the distribution and directionality of light that enters the pupil of an eye located there. The color of an object is related to the distribution of wavelengths of this light.

**Photons or Waves**

The idea that a wavelength of light can be associated with the behavior of an individual photon has its origins in the early 1900s with the work of Max Planck. Jenkins and White (1957) noted that

> ... visible light of ordinary intensities contains so many photons that their average behavior is accurately given by the wave theory provided that the interactions with individual atoms of matter do not involve quantized energy states of the latter (p. 629).

Light consists of small packets of highly localized energy. This packet, which we have been properly calling a photon, is able to “... communicate all of its energy to a single atom or molecule” (Jenkins and White, 1957, p. 611). When discussing the optics associated with light we will make reference to the wave theory, and when we discuss the absorption of light by the receptor photopigments we will make reference to the particle theory of light. In anticipation of using both theories, we introduce them briefly in this chapter.

If a photon moves with frequency \( \nu \) and in a plane perpendicular to its direction of travel at the speed of light \( c \), then some distance will be traversed during the time required for the particle to move through one cycle. This distance is called wavelength and it is inversely proportional to the frequency: \( \lambda = c/\nu \) (Fig. 3.1). When considering light moving as a sinusoidal wave it is necessary to define the concept of a wavefront. A wavefront is “an imaginary surface representing the locus of points in wave motion for which, at a given instant, the phase is the same” (Cline, Hofstetter, and Griffin, 1980).

An experiment demonstrating the wavelength nature of light goes as follows. Imagine a beam of light passing through a pinhole aperture (\( a_p \)) and that this light then is incident upon a pair of very narrow slits, \( a_s \) and \( a_s' \) (Fig. 3.2). The distribution of light that results was first shown by Thomas Young (1807) and is represented as an interference pattern represented on the far right of Figure 3.2. This interference pattern can be understood by recognizing that the light, after
Figure 3.1  Relations between wavelength and frequency of vibration. In $10^{-14}$ s, light will travel about 3000 nm. Extreme violet light (375 nm) vibrates through 8 cycles during this time, so the distance $\lambda$ that it travels during one cycle is $3000/8 = 375$ nm. Extreme red light vibrates more slowly, covering 4 cycles during this time; the distance that it travels is $3000/4 = 750$ nm. The distance that light travels during one cycle of vibration defines its wavelength.

traversing slits $a_1$ and $a_2$, forms wavefronts. These wavefronts produce constructive and destructive interference patterns in the plane labeled C. In those places where the two wavefronts are in phase, constructive interference occurs and the light will be bright. Where the two wavefronts are out-of-phase, destructive interference occurs and the light will be dim. This experiment does a good job of demonstrating the wave nature of light. However, the full story is not so simple.

Feinberg (1968) reported that G. I. Taylor conducted a version of the Thomas Young experiment at the University of Cambridge in the early 1900s using extremely low exposures of several months duration, and found an interference pattern on the photographic plate used to collect the light. In 1967, Pfleegor and Mandel, at the University of Rochester, reported doing this same kind of experiment under conditions where the rate of light arrival at the receiving plane was so slow that light interaction was not possible. Very sensitive detectors were used to register where each photon arrived at the plane behind the slits. Over a very long period of time, the distribution of photon incidence that built up was the same as that obtained under the more usual high-intensity conditions where interactions between photons seemed possible. The implication, as Dirac (1958) had earlier expressed it, is clear: “Each photon then interferes only with itself.” Dirac went on to say that “interference between two different photons never occurs.” Although Pfleegor and Mandel’s experiment fails to prove the second statement, their result is consistent with it. Feynman (1965) gave a different and more intuitively palatable explanation. He contends that what builds up on the receiving plane is a distribution of the probability of photons hitting various points along the receiving plane. The brighter areas represent areas of high-probability hits and the darker parts areas of lower-probability hits. For the condition where there are very few photons over a period of time being emitted, he contends that they arrive like discrete particles, but the probability of their arrival is determined as the intensity of waves would be. Consequently, photons sometimes behave like particles and sometimes like waves. They “... behave in two different ways at the same time” (Feynman, 1965, p. 138).

Wavelength and Hue

The wavelengths of photons to which the eye is sensitive are in the range of about 380 to 750 nm. Although the perception of hue cannot be reliably mediated by a single photon, the use of large enough numbers of them (high intensities) under otherwise appropriate
conditions leads to a reliable correspondence between wavelength and hue. The shortest perceptible wavelengths appear violet, or reddish blue. As wavelength is increased, the reddish component diminishes and disappears at about 470 nm, at a point called psychologically unique blue. (Recall, from Chapter 2, that this is a blue that is neither reddish nor greenish.) As wavelength is further increased, the appearance of blue becomes progressively more greenish; a balanced blue-green is achieved around 490 nm and then the green component predominates and unique green is reached in the range of about 500 to 515 nm. The longest wavelengths of the spectrum appear to be nearly (but not quite) a pure red (Hurvich, 1981; Abramov, Gordon, and Chan, 1991). Shortening the wavelength from 700 nm introduces a greater yellowish component; a balanced red-yellow (orange) is seen at about 600 nm. Further shortening of wavelength causes the red component to diminish until psychologically unique yellow is reached at about 575 nm. The range between about 515 and 575 nm appears as yellow-green blends and a balanced yellow-green occurs at about 550 nm.* The reader may wonder why we cannot be more precise about the wavelengths that produce these hues. In point of fact, it is possible to precisely determine the hues that individual observers will report at specific wavelengths (Boynton and Gordon, 1965). However, inter-observer variability requires the less precise statements we make above when referring to human observers in general.

Refer to the color diagram of Figure 2.4 and indicate around the color circle the wavelengths that correspond to the psychologically unique hues and the balanced blends. Note that there is no wavelength corresponding to the balanced sensation of reddish blue and there is no wavelength which corresponds to unique red — e.g., a red with no red or yellow component.

**SOURCES OF LIGHT**

**Natural Illumination**

No creature — not even a cat — can see in the dark. All visual perception demands that a source of illumination be present to irradiate the objects that are seen. Sunlight, which has presumably always been available to guide the evolution of eyes, is still very important. The solar radiant energy begins as gamma radiation comprised of wavelengths at least a million times too short to see. This radiation is spread out into longer wavelengths "by absorption and re-emission processes throughout the sun's bulk" (Henderson, 1977, p. 15). The distribution of wavelengths in sunlight is further altered following interaction with the earth's atmosphere. Figure 3.3 shows how extraterrestrial sunlight has its spectrum altered by absorption and scattering. By the time sunlight reaches the earth, all wavelengths are still richly represented throughout the visible spectrum.

**Artificial Illumination**

The production of artificial light originally required that something be burned in open air. The flame of a candle is an example of such a source. Its spectral output in the shorter wavelengths of the visible spectrum is deficient, relative to that of daylight. In general, the same is true for incandescent lamps (ordinary light bulbs) in which a filament is heated until it glows. The gas-filled enclosure is designed to preserve the life of the filament. When operated at very low current, no visible radiation is produced by such a lamp. As the applied voltage is increased, causing an increase in current flow through the filament, its tempera-
Figure 3.4  Spectral distribution of light emitted from a “complete radiator” (which tungsten closely approximates) as a function of temperature. These curves are normalized at 560 nm and, therefore, do not show that the absolute amount of energy emitted grows, at all wavelengths, as temperature is increased. Ordinary tungsten lamps operate in the range (shaded) from 2500° to 3000°. Over this small range, the efficiency of such lamps increases from about 8 to 22 lumens per watt. (From The Science of Color, 1953, p. 261.)

The highest temperatures, but at the cost of a drastic shortening of the life of ordinary light bulbs. The quartz-iodide lamp, now used in many slide projectors, automobile head lights, ordinary household lighting, and laboratories, solves this problem by causing much of the tungsten that leaves the filament to redepot itself back upon the filament, rather than upon the inside wall of the lamp enclosure.

Good color rendering depends on a continuous spectrum like that provided by sunlight or incandescent lamps. Color rendering refers to the effect a light source has on object color appearance. Incandescent lamps generate large amounts of infrared radiation, resulting in more heat than light. This limits the efficiency that can be provided by this kind of artificial light, as measured in lumens per watt.

The lumen is a measure of the amount of visually effective light. The watt, a unit of physical power, refers in this case to the energy supplied as input to the lamp, which is, of course, what the consumer pays for. It is not surprising that when fluorescent lights, which are much more efficient, were developed in the 1950s, they almost immediately started to become popular for commercial lighting and are now widely used for this purpose as well as home lighting.

A fluorescent lamp contains a mercury vapor which, when energized electrically, emits ultraviolet radiation that itself is invisible. The manner in which this radiation is converted into visible light is explained by LeGrand as follows:

... the inside of the envelope, or tube, is coated with a fluorescent layer, which absorbs the 253.7 nm radiation and emits, as a result, a continuous spectrum of longer wavelengths. [T]he spectral emittance of the fluorescent light is a maximum at about 440 nm for a coating of calcium tungstate, 480 for magnesium tungstate, 525 for zinc silicate, 595 for cadmium silicate, 615 for cadmium borate and 665 nm for magnesium germanate. Usually about 16% of the energy consumed by the lamp reappears as fluorescent light (1968, p. 25).

Fluorescent lamps produce about 60 lumens per watt. (See Figure 3.4 for data on tungsten incandescent sources.) The spectral lines of a fluorescent tube, which may contain a mixture of these substances, are merged so that there is a continuity of radiation throughout the spectrum. Especially for the most efficient lamps, which are deficient in long-wave radiation, fluorescent lamps are poor for color rendering. The subtle colors of human complexions are not improved by such fluorescent lamps. Incandescent sources, which are rich in long wavelengths, are often used to spotlight roast beef in areas otherwise lit by fluorescent light. Otherwise an expensive red roast looks like a cheap overcooked cut, and even the completely uncooked meats in the supermarket can look grayish and unappetizing.
There are many other light sources in common use these days. A full treatment of these is not necessary here, and can be found, for example, in the *Illuminating Engineering Society Handbook*. These other sources include arc lamps, like the xenon source used for commercial motion picture projection (and in many vision labs), and the sodium vapor lamp, sometimes used for highway illumination because of its exceptional efficiency. The spectral lines of the xenon arc are greatly smeared under pressure, resulting in an excellent spectral distribution for color rendering. The low-pressure sodium vapor lamp, on the other hand, emits mostly yellow light from a narrow band of the spectrum and only very weakly elsewhere; nearly total color blindness occurs when objects are seen illuminated by its rays. High-pressure sodium, which is often used for street lighting, has better spectral properties because of the pressure broadening in vapor of the spectral lines.

**WHAT HAPPENS TO LIGHT WHEN IT ENCOUNTERS VARIOUS MEDIA?**

When light travels and encounters a medium other than that through which it has been traveling several things can happen. It can be transmitted, meaning it passes through the medium relatively unimpeded. Light can be reflected, which is what we commonly experience when looking into a mirror. If the substance is appropriate, the light will become completely absorbed. It can be refracted, which gives a rod its bent appearance when partially submerged in water. When light encounters substances that are not completely transparent it can be scattered. These effects on light are represented in Figure 3.5. One other action of light will be discussed and that occurs when light passes quite close to an opaque edge. When this happens a process of diffraction occurs. Each of these optical effects will be discussed in more detail in the following.

**Transmission**

When light moves from one location to another it moves through some medium. That medium might be glass, air, the various components of the eye, or even a vacuum. When this occurs we speak of light being transmitted or the transmission of light (Fig. 3.5). So far nothing has been discussed about the effect of the medium through which light travels. Except for a vacuum, there is no such thing as a perfectly transparent medium. The fact that light requires no medium for its transport is a fact only grudgingly conceded by physicists in this century: the idea of an "ether" that supposedly existed for this purpose, even in a vacuum, had long been in vogue. Experimental evidence capable of testing, yet failing to support, the ether concept finally led to its demise (the famous Michelson-Morley experiment).

Transparent media have an effect on light because they contain atoms that interact with photons. Some of the atoms absorb photons (we will deal with absorption below). Others change the flight path of a photon, and this is called scatter (see below). The flight paths of photons that once having entered a medium are able to pass within it without change of direction define the *image-forming rays*, and these are almost always the ones that are important for vision. Image-forming rays that pass through the atmosphere are little altered by it; it is also the case that photons traveling along these paths do so with negligible reduction of speed compared to that in a vacuum. Apparently these photons get through the widely spaced molecules of the atmosphere without interacting with them.

Transparent media other than the atmosphere, such as glass, have a much higher molecular density and it is not possible for photons to pass through (even though very few of them may be absorbed) without interacting with the atoms of the glass. But these interactions produce, in addition, a very important result, namely a reduction in the velocity of the photon compared to what it would be in
air. This is not a small effect: ordinary glass or water will reduce the speed of light by about a third. The speed of light in a vacuum divided by the speed of light in a medium defines the index of refraction of that medium (1.33 for water).

**Reflection**

Most of the time we see objects only because they reflect light to a greater or lesser degree than their backgrounds. Offhand it might seem that reflection should be a rather simple matter. From the subjective view of Chapter 2, glossy surfaces reflect light at the same angle of incidence and without any change of color. Whereas glossy surfaces are very smooth, matte surfaces have tiny surface imperfections that cause light to scatter and somehow have the ability to change color.

Most writers who deal with the topic of reflection, even at the highly technical level that is necessary to understand the principles of color printing or photography, assume that the reflected light from a surface is some portion of that which was incident. Light is incident upon the color print: some of it passes through the outer glossy surface and through the layers of selectively absorbing dyes. The spectral distribution of the light (numbers of photons as a function of wavelength) is altered by the double transfer through the dyes, both before and after reflection from the white paper beneath. There may be internal reflections, which is a problem of scatter (see below), and there are many other technical problems to deal with, but surely the light that is reflected from the print is the same light that illuminated it.

**Absorption**

On the contrary, the physicist Victor Weisskopf writes:

The overwhelming majority of things we see when we look around our environment do not emit light of their own. They are visible only because they reemit part of the light that falls on them from some primary source, such as the sun or an electric lamp. What is the nature of the light that reaches our eyes from objects that are inherently nonluminous?

In everyday language we say that such light is reflected or, in some cases, transmitted. As we shall see, however, the terms reflection and transmission give little hint of the subtle atomic and molecular mechanisms that come into play when materials are irradiated by a light source. (Weisskopf, 1968, p. 60.)

Reemission implies that the photons reflected from an object are not the same ones that are incident upon it. Nevertheless, with the relatively rare exception of fluorescent materials, such physical theory states that the wavelength of the emerging photon is exactly the same as that of the incident one. The numbers of emerging photons never exceed the numbers of incident ones. The time delay involved in the substitution of one photon for another is too short to measure. Therefore, so far as the potential visual effects of emerging photons are concerned, they might as well be some of the same ones that were incident upon a surface. No conceivable detector, whether eye or otherwise, could tell the difference. Therefore, we shall assume that any emerging reflected photon is the same as one of those that was incident, meaning that individual photons reflect without losing their identity. Making this assumption allows us to trace the fate of a hypothetical individual photon as it interacts with matter, both outside and inside the eye.

Recall from Chapter 2 that the most important property of a surface for perceiving its color is diffuse spectral reflectance. This is a statement about how the probability of a photon being reflected from a surface, in an unpredictable direction, varies depending on the wavelength of the incident photon. Although much remains to be learned about how surfaces in nature manage to do this, the fact that they do is crucial for color perception.

**Refraction**

When a beam of light enters some medium, for example a dark glass, not all of it will emerge out of the other side (Fig. 3.5). Some of this light will become scattered and emerge from the glass in unpredictable places (see discussion on scatter below). Some of the light is absorbed by the atoms contained in the medium and is converted to heat: that which is converted to heat is said to be absorbed. The more transparent the medium is, the less absorption will take place. The extent to which absorption takes place is wavelength dependent. For example, if you take a monochromatic light of say 470 nm (unique blue for many people) and shine it on a filter whose maximum spectral transmittance is at 470 nm, this light will pass through with little absorption. If, on the other hand, the 470 nm light is shone on a filter that has a maximum transmittance at 650 nm (a red filter), then a great deal of this short wavelength light will be absorbed.
outside continues at its original rate. The only way that a wavefront can enter the glass and maintain its integrity is to change its direction. An
analogy may help here: imagine two wheels mounted on roller bearings on opposite ends of an axle, entering sand from a concrete roadway. If the direction of entry is perpendicular to the edge of the roadway, both wheels will leave the roadway at the same time and will be slowed in the sand by the same amount, so that the unit as a whole, defined by a line perpendicular to the axle, will continue to move in its original direction. But if the entrance is oblique, the sand will slow the rotation of the inner wheel before the outer one is affected. In order to

preserve its integrity, the unit must change direction as it enters the sand. The more formal treatment of refraction invokes Huygen's theory of secondary wavelets and the interested reader is referred to a textbook on optics (e.g., Jenkins and White, 1957; Falk et al., 1986).

Refraction is what allows images to be formed in eyes and cameras. As Kepler first understood, positive lenses can be used to cause bundles of diverging light, incident upon one surface of a lens, to converge again on the other side to form an image, which must be upside down, as shown in Figure 3.7. (Refraction will be dealt with again at the end of this chapter.)*

Figure 3.7 Nodal point system for determining the location of a retinal image.

(Refraction will be dealt with again at the end of this chapter.)*

Scatter

Scatter (Fig. 3.5) occurs whenever the reradiation of photons by the molecules of a transmitting medium is other than in the forward direction. Such photons become useless for, and often degrade, spatial vision. The light that we see when a beam pierces a smoky room is visible only because of scatter. In a perfectly transmitting medium, beams of enormous intensity could pass just before our eyes and we would not see them. There is appreciable light scatter over long distances even in clear atmosphere, and a great deal of it occurs under other conditions, especially in fog. There is a surprisingly large
amount of scattered light in the eye itself, which has significant effects for vision. An extreme example of ocular light scatter occurs when the lens of the eye becomes cloudy, which is called a cataract. This condition is common in the elderly but can occur at any age.

When scattering particles are large, as they are in the eye, scatter is largely independent of wavelength and is concentrated in a forward direction. When the particles are small, as in the atmosphere on a clear day, shortwave photons are much more likely to be scattered than long-wave ones; this is the physical basis for the blue of the sky.

**Diffraction**

If a light encounters an opaque (nontransparent) object, it will be either absorbed or reflected. If it passes the edge of such an object at a considerable distance, the presence of the remote object will have no ability to influence the light path and it will go by just as it would if the object were completely removed from the scene. But if a light passes very near the edge of a surface, it will appear to bend around the edge. This is called **diffraction**. Huygens, in the 17th century, explained this phenomenon as follows. Invoking the wave theory of light, one can consider light as a series of wavefronts moving along the path taken by the light. Each point on a wavefront acts like a new spherical wave source. As can be seen in Figure 3.8, when the wavefront encounters an edge, the curved part of the front will contain a new source that sends light off on an angle away from the original direction of light propagation. Some of this light is sent behind the opaque surface edge, giving the appearance of the light "bending" around the edge.

Diffraction sets an upper limit on the ability of any optical system, including the eye, to image each point as a point. In the pin-hole camera, diffraction is very great and the image quality is poor. As the pupil of the eye becomes larger, the image blur due to diffraction becomes less. This relates to the fact that opening the pupil allows a smaller proportion of the incoming light being processed by the eye to interact with the edge of the pupil.

**THE FATE OF A SOLAR PHOTON**

Consider a photon, on its way toward the earth from the sun, which ultimately might enter an observer's eye, thus contributing to vision. Unless the photon is traveling through outer space in the direction of the earth, the initial probability that it will enter into an earthling's vision is nearly zero. To a first approximation outer space is a perfect vacuum; therefore, the path of a photon will be in a straight line (neglecting weak magnetic field effects) and it will miss the earth. Photons that miss the earth in this manner are most unlikely to have a second chance, with the exception (which we shall ignore) of some of those that travel in the direction of the moon or other objects in the solar system (see path a in Fig. 3.9) from which they may reflect.

Next consider photon b, which is headed for the earth at a grazing angle. The greatest probability by far is that it will pass unmolested through the atmosphere. If so, it will emerge from the other side of the atmosphere and cannot possibly contribute to visual stimulation. Such photons must have their direction of travel altered to be potential contributors to vision. This happens fairly frequently. If a photon interacts with an atmospheric molecule two possibilities exist. It may be absorbed by the molecule, increasing the latter's agitation and thereby adding its tiny share to atmospheric temperature. Such a photon will travel no farther and no longer is in contention as a visual stimulus. A second possibility is scatter, which can occur in any direction within the full 4π steradians of solid angle surrounding the molecule, including straight ahead (in which case the scatter would be undetectable and might as well never have occurred), and straight back along the path of incidence. Where scatter is concerned, the probabilities involved are very complex and depend on the wavelength of the photon as this relates to the properties of the molecule with which it collides. For a photon incident upon the earth's atmosphere at a grazing angle, the result is that the photon, which would
almost certainly have missed striking a planet free of atmosphere, instead has a finite probability of being scattered toward the surface of the earth (c', c in Fig. 3.9)

Consider next photon d headed directly toward the surface of the earth. It may also be absorbed or scattered before reaching the earth. If scattered, it may be directed into space (d') or toward a different terrestrial point than that toward which it started (d). On a clear day, the greatest chance is that the photon will escape collision with atmospheric molecules and continue on its trip to earth.

From the standpoint of an observer on earth, a group of photons that originate from the same place may reach the eye in more than one way. We do not, and should not, look directly at the sun (although its rays very often enter the eye in peripheral vision while we are trying to look somewhere else). Imagine that the eye is pointed straight toward the sun (e). Given the origin of a photon at a particular point on the sun, there is a certain probability that, having traveled through space and having avoided collision with atmospheric molecules, it will continue directly to the eye. More important is the fact that sunlight illuminates everything around us, and some of this light is reflected toward our eyes. Few objects are self-luminous; most are seen as a result of reflection. So this is another path that an individual photon might take: from sun to object to eye. Yet another photon may start out in a direction deviant from that which would stimulate the eye directly. Instead, it is scattered in the atmosphere and, therefore, appears to be coming from some place other than its original source. Scattered light is what makes the sky light up. Almost everyone has seen, on television or in photographs, the effect of an absence of such light scatter on the moon, where the sky is jet-black even at midday because the moon lacks atmosphere. A final possibility is a scattered photon that strikes an object and is then reflected or scattered into the eye. Most objects that are seen in the shade on a sunny day owe their visibility to this effect: on the moon, they generally would not be visible. On a cloudy day, all objects owe their visibility to illumination provided by scattered light.

**THE IMPORTANCE OF DIRECTION**

A prerequisite to gauging the color of an object is to discern that the object exists in the first place. To gain the recognition at a distance that is characteristic of such object vision, it is necessary somehow to extract salient information from the dense pattern of rays that are found in any complex real-world environment. To do this requires spatial vision, which may be defined as an ability to detect the discontinuities in such patterns of rays caused by the presence of the object.

Imagine yourself in a classroom illuminated by a combination of light from the window and overhead fluorescent fixtures. Consider that you are sitting somewhere in the middle of this room, and that a white piece of cardboard is attached to the wall at the front of the room. At the location of the pupil of, say, your right eye, there will exist a complex array of photon flight paths, or rays — some coming directly from the sources of radiation, others reflecting from the various surfaces in the room, including the cardboard. Suppose now that an arrow, about 1 m long, base down and tip up, is drawn on the cardboard with a green felt pen. If anyone were to ask "what has just been drawn on the cardboard?" all will agree that it is a green arrow.

The usual textbook explanation of how this image inversion happens is shown by the ray diagram in Figure 3.7. The arrow is shown at the left with just two rays emerging from it — one from the base and one from the tip. These rays cross in the eye and produce an image, which is upside down, upon the retina. The image is green, and the arrow is seen. This explanation is inadequate in the extreme. In the first place, the green arrow, which is not self-luminous, does not have the capacity to reflect photons only in the direction of the eye. Second, the light reflecting from it comes from all along the length of
the arrow, not just from the ends. Third, the retinal image must be processed; its existence does not "explain" vision.

Pretending for the moment that the arrow is self-luminous, let us concentrate on the light coming from its tip. A critical point is that photons emerge from this point in space in all possible directions within the half-sphere in front of the cardboard. There is not just one ray headed magically toward the middle of the eye as shown in Figure 3.7. (If this were so, moving the head slightly would cause the arrow to disappear; actually, of course, one can move freely around the room and see the arrow from just about any vantage point.) A truer situation is diagrammed in Figure 3.10. With the eye in any particular location, the rays of interest are the diverging ones that strike the cornea of the eye over a range of locations such that the rays passing through the cornea also pass through the pupil of the eye. We ignore, for purposes of analysis, all other rays.

We have known, since Kepler, that the optics of the eye brings this bundle of rays to a focus on the retina where the so-called retinal image of the arrow tip will be formed. Because of the diffraction limitation and other factors, it is both theoretically and practically impossible for an optical system to image a point exactly as a point. Instead, the point will be imaged on the retina as a more-or-less Gaussian (bell-shaped) spread function. Nevertheless, it will be convenient to imagine that there is a point image on the retina, keeping in mind that this represents a serious oversimplification.

What then is the meaning, if any, of the diagram in Figure 3.7? The explanation has to do with the concept of the nodal point in optics. The behavior of any coaxial optical system, however complex, can be predicted by a model of the type shown in Figure 3.11. Given the object point, two nodal points, and a known location of the image plane, the approximate location of the image can be calculated by drawing a line from the object to the first nodal point, and another line from the second nodal point, parallel to the first line, until it intersects the image plane. The eye is an unusual optical system, because the rays entering it from air proceed to a denser medium from which they do not again emerge. Partly for this reason, the two nodal points of the eye are very close together; and, although their locations vary slightly depending on the state of accommodation of the eye, they may be considered for many practical purposes as being coincident, located about 7 mm behind the vertex of the cornea of the eye. Assuming a single nodal point means that the location of an image on the retina of the eye can be easily determined to a first approximation. Simply draw a line from the object, through the nodal point, and determine where it strikes the back of the eye. But no photon actually follows such a path, unless it passes along the optical axis of the eye. The actual path is usually much more complicated because refraction takes place at the corneal surface and at a number of other places within the eye where there is a sudden change in the index of refraction. To represent the formation of an image in the eye as if actual light rays cross at the nodal point is a useful concept for an approximate calculation of retinal image location and for defining the visual angle subtended by an object. If taken with respect to the nodal point, visual angle is the same outside as inside the eye. Figure 3.12 shows that, because of similar triangles, the angle subtended by the image on the retina is the same angle as that subtended by the object at which the observer is looking. Using simple trigonometry allows one to determine this angle by knowing the size of the object and its distance from the eye.
The Visual Stimulus

The Importance of Direction

Figure 3.12 The visual angle of an image on the retina can be calculated by measuring the angle subtended by the object outside of the eye. \( \theta = \theta' \) because \( \text{abc} \) and \( \text{nbc} \) are similar triangles. Therefore, for a given \( \theta \), the subtense of the retinal image depends on the ratio of \( d' \) to \( d \).

The fact that the arrow on the cardboard is not self-luminous complicates the matter considerably. Imagine a nondirectionally sensitive photocell at the location of the eye, and suppose that a reading of its output is taken before the arrow is drawn on the cardboard. After the arrow is drawn, the number of photons per unit time received at the photocell is decreased, but by how much? It is worth taking time out to do the calculation — at least approximately.

To simplify the problem, we will imagine a black object on a white background, the latter consisting of the half-sphere of Figure 3.13 with a nondirectional photocell located 10 meters from the back of the half-sphere. Assume that the surface of the sphere is uniformly illuminated and, for the moment, that the green arrow is replaced by a nonreflecting black line, 0.002 m wide and 0.3 m in length. All areas of the sphere will affect the photocell equally, except the area that is black. The area of the black region is 0.0006 m², whereas that of the hemisphere is 2\( \pi r^2 \), which is slightly more than 600 m². The result is that the decrease in the rate of photon incidence upon the photocell, caused by the black line on the sphere, is less than 1 part in a million.

But the eye can do better than this. The line so far described subtends a visual angle of about 0.35 minute of arc. A black line of this width can be discriminated very easily. Hecht, Ross, and Mueller (1947) reported that under ideal conditions they could see a wire 1/16 inch in diameter at a distance of 1 mile. This works out to about 0.5 second of visual angle. Thus, for an easily visible line, a reduction in the amount of light received at the photocell could be less than 1 part in 10 million. No nondirectional device could possibly discriminate such a small difference; the ability of the eye itself to discriminate variations in the intensity of a uniform field is more like one part in a hundred (see Chapter 6). The remarkable fact that the observer easily sees such a line must therefore be critically dependent on the ability of the eye to sort out photons according to their direction of incidence and to disregard most of these as irrelevant to the task at hand. In essence, this is what the formation of a retinal image accomplishes by translating differences in angle of incidence of photons upon the eye into spatial location upon the retina.

There is, of course, much more that could be said on the matter of spatial vision. For example, how do we localize an object in depth? How do we judge the size of an object? How does the visual system deal with the inevitable blur of the retinal image caused by the fact that points are not exactly imaged as points? In this book on color, we will not deal much further with these interesting issues. It is hoped, however, that the following point has by now been well established: Without pattern vision there could be no vision of real objects, and because color is usually a perceptual property of real objects there can be no study of the color of real objects without becoming involved to some extent with the problems of pattern vision.
WAVELENGTH, PHOTON ENERGY, AND RETINAL IRRADIATION

One of the triumphs of twentieth-century physics has been the clarification of the relation between the wavelength and the energy of the photons that make up light at that wavelength. (The reader is reminded that each photon also has wave properties.)

The quantitative relations between the wavelength of a photon and its frequency of vibration have already been mentioned. Given that all photons travel at the same velocity in a given medium, whatever their frequency, it is perhaps intuitively clear that those photons of higher frequency are more energetic than the ones of lower frequency; it turns out that the two quantities are directly proportional to each other. This, then, is the picture to bear in mind: longwave photons are of lower frequency and are less energetic than shortwave photons.

Probably the most basic property of a photon is its frequency. This does not change as a photon enters a medium of higher index of refraction. Because the photon now moves more slowly, its wavelength must shorten. No energy is lost. Therefore a photon of red light at 650 nm will have its wavelength shortened to 487 nm inside a medium, such as the eye, with an index of refraction of about 4/3. Frequency, which is $4.6 \times 10^{14}$ s$^{-1}$ outside the eye, is the same inside. Despite the fact that frequency is a better metric for measuring the spectral aspect of light than is wavelength, the use of wavelength in visual science is so well established that we will also follow this convention.

In describing various experiments to be reported in chapters to follow, it is necessary to decide in what units of intensity to report the visual stimuli that have been employed. A bewildering variety of units has been used for this purpose. The subject of photometry deals with the definition of such units, and this is required because the eye has a sensitivity that differs depending on wavelength of the photons that are absorbed in the retina. To specify the visual stimulus strictly in terms of the numbers of photons incident upon the retina would be meaningless, unless the wavelength distribution of these photons were known so that their visual effectiveness can be evaluated.

There exists a unit of retinal illuminance, which is the density of light incident upon the retina, called the troland (td). The usual definition of the troland requires first that the entire system of photometry be developed. One of the better photometric tutorials is found in LeGrand (1968). Chapter 4 of Wyszecki and Stiles (1982), provides another excellent treatment of photometry.

We shall avoid such photometric details here simply by noting that, at a wavelength of 555 nm, photons have a frequency of $5.4 \times 10^{14}$ Hz and an energy of $3.58 \times 10^{-19}$ erg. This energy results in approximately one million photons per second per degree of visual angle, incident upon the retina, to produce a retinal illuminance of 1 td. A general equation relating the number of trolands ($N_t$) to the number of photons ($N_p$) per sec per deg is:

$$N_t = 8 \times 10^{-7} N_p Q(\lambda)$$

where $Q(\lambda)$ is a measure of the relative spectral sensitivity of the eye on a quantal basis (see "Energy-vs. Photon-Based Sensitivity" in Chapter 5, p. 128). This in turn relates to $V(\lambda)$, the photopic luminosity function (see Note 3, Chapter 8, p. 354 and Appendix, Part 1), by

$$Q(\lambda) = V(\lambda) \frac{555}{\lambda}$$

where $\lambda$ is in nanometers. $Q(\lambda)$ has a value of 1.0 at a wavelength of 555 nm. Because this is the wavelength of highest sensitivity for the light-adapted eye, $V(\lambda)$ has a value of less than 1 at all other wavelengths. The total variation of wavelengths of visible photons is less than two to one. Late in the nineteenth century it was established that the visible spectrum is but a narrow band in a total spectrum of electromagnetic radiation that covers some 22 logarithmic units (decades), as shown in Figure 3.14. To deal with very long wavelengths in a manner analogous to the way it handles visible ones, an eye would have to be scaled upward proportionally in size. To deal with very short wavelengths an eye would have to be microscopically small. Moreover, it is not likely that x-rays, which pass easily through most objects that are significant to us, would be effective messengers about the outside world. Visible light apparently has just the right wavelengths to reflect from objects in useful ways and to permit the evolution of a compact and efficient pickup device, the eye.

DISPERSION AND CHROMATIC ABERRATION

Although Kepler was the first to understand in a general way how lenses work (as we saw in Chapter 1), the principles of light refraction that underlie their function were not quantitatively understood until late in his lifetime. In notes that were not discovered until their author’s death, Willebrord Snell wrote in 1621 that "the place of the
Figure 3.14 The visible spectrum is a relatively narrow band in the total spectrum of electromagnetic energy, as shown here (from Riggs, 1965).

image follows in each case a well-defined perpendicular in such a way that always the incident ray observes to the place of the image from the point of incidence its own perpetual proportion" (Sabara, 1967, p. 99). What this means is illustrated in Figure 3.15a. Ray AB, incident upon interface MN (for example, that between air at the top and glass at the bottom), is refracted as shown. If a perpendicular to the interface is erected anywhere to the right of B, the ratio BD/BE is constant, no matter what the angle of incidence of AB with respect to the interface MN. In 1637, Descartes published the law of sines, usually referred to as Snell's law, in the form that we now know it. For this purpose, the simpler construction shown in Figure 3.15b was used; the relations that Snell discovered can be expressed instead as:

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]  

(3.4)

where \( n_1 \) and \( n_2 \) are designated as, and in fact define, the relative refractive index of each medium.

Snell's law permits an extremely accurate calculation of the direction of the refracted ray, provided that the indices of refraction of the media are known. Conversely, measurements of the deviations of such rays provide an easy and practical way to measure the relative indices of refraction of any two optical media. It will be recalled that these relations can, in principle, also be determined by measuring the relative speed of light in the two media. But this is not easy to do, and nothing was known anyway about the speed of light at the time Snell made his discovery.

Newton's dispersion of white light into its spectral components shows that refraction varies with wavelength. When light slows down, for example when entering glass from air, the photons that comprise that light slow to different degrees, depending on their wavelengths. The photons with the highest frequency (and which, therefore, have the shortest wavelengths) slow down the most and show a larger change in direction than those with lower frequency. Therefore, the index of refraction of an optical medium is not a single value but a continuous series of values that vary as a function of the wavelength of the light.

But the full story is yet more complicated. The rate at which the refractive index varies with wavelength differs from one optical medium to another. The higher the rate, the greater the dispersive power of the medium. Because refraction varies with wavelength, whatever the dispersive power, a simple lens always refracts short-wave light more than long-wave light, causing chromatic aberration to occur. It is common to correct for this in manmade optical systems by judiciously selecting optical glasses of particular refractive and dispersive powers which can be used together in multielement lenses.
Perhaps because eyes are not made of glass, no such correction for chromatic aberration has evolved. If the eye is accommodated (focused) on a distant red target of wavelength 700 nm, a distant violet one of 400 nm will be seriously blurred (Fig. 3.16). If focus is held on the distant red target, the violet one must be brought to within about 0.5 m of the eye before good focus is achieved. This means that normal eyes are seriously myopic — in the vernacular, “near-sighted” — for distant blue targets, and, therefore, there is no possibility that the mixed rays from a white target can all be optimally focused upon the retina. Because there is no way to accommodate for distant blue targets, it is not surprising that the eye tends to accommodate instead for longer wavelengths than this, allowing the short-wave components of the retinal image to be seriously blurred.

Yet we do not ordinarily perceive the expected effects of such chromatic aberration, which would be a visual world whose edges are tinged with chromatic fringes. Why not? This is an important problem for color vision, and we shall return to it in subsequent chapters. Leaving the details for later, the following factors seem to be involved in the attempt to understand this interesting problem.

- Selective absorption occurs in the eye media, reducing the effectiveness of blue light and thereby effectively shortening the visible spectrum (Chapter 5).
- The short-wavelength-sensitive cones enter importantly into the perception of hue but very little into the perception of contour. Because these cones absorb mostly short-wave light this is in effect another spectrum-shortening device, but one that is selective for contour (Chapters 5, 8, and 9).
- The Stiles–Crawford effect, attributable to the directional sensitivity of the cone photoreceptors, reduces the effectiveness of rays entering the margins of the pupil (Stiles and Crawford, 1933a); these marginal rays produce the greatest amount of chromatic aberration (Fig. 3.16).
- When prisms are mounted before the eyes, the chromatic fringes that they produce upon the retina are at first very evident in sensation. But if the prisms are worn for a long time the fringes become very much less evident and may even disappear. This indicates that neural machinery exists, which is capable of compensating for consistent relations between fringes and contours, somehow expelling the part of the message that carries no real information about the outside world (Kohler, 1962).

**SUMMARY**

The use of physical concepts to help understand human color vision is important, because it avoids a tautology that is inevitable if, as is often done, the stimulus for vision is described according to how things look.

Of the various ways to regard light, its conception as a collection of swiftly moving photons is especially useful for vision. The frequency of each photon is inversely related to its wavelength; this frequency carries the initial chromatic message. Among the properties of light that are important for vision is its tendency to move in straight lines except when scattered, diffracted, refracted, or reflected. The optical system of the eye causes diverging light from points in visual space to converge and form an image at the retina. Spatial vision, thus mediated, is essential to color vision because the latter normally relates to, and is affected by, specific regions of space.

Reflection is important because the visual properties of object surfaces, including their colors, depend upon it. Diffraction limits
the optimal quality of any image, including the one in the eye. Scatter is helpful because the diffuse light that it provides from the sky helps to fill dark shadows. Refraction is essential for image formation in eyes and cameras.

The direction of photon travel is critically important for vision. As an example it is shown that unless the directions of incident photons can be sorted out, the percentage of change in the total number of photons reaching the eye, from an easily visible target, is orders of magnitude too small to register.

The relation between the wavelength and energy of photons is easily and clearly understood within the framework of modern physics. The energy of a photon does not change as it moves from one medium to another, nor does its frequency of vibration. In passing from air to glass, for example, a photon slows down and its wavelength decreases.

The standard unit of light intensity to be used in this book is the troland, which is proportional to the number of photons per second per square degree incident upon the retina, weighted according to the photopic spectral sensitivity of the visual system.

The eye is subject to a serious amount of chromatic aberration, which nevertheless seems to have no seriously deleterious effect upon spatial vision.

NOTES

1 There is no way to be certain that magnetic fields could not tell us a great deal about what we require to know about the physical world. However this may be, we certainly know that vision provides much of our information about the outside world, though perhaps not quite the 90% once claimed by the American Optometric Association. Because vision is so important it is reasonable to expect that light interacts with objects in especially useful ways, and that we have been able to evolve sensory devices that are able to extract whatever is most important from the radiation patterns in which we find ourselves imbedded.

2 From time to time, one sees reports that colors can be discriminated by some people through the tactile sense. A blindfolded person surely could tell the difference, say, between a white cat and a black cat in the sunlight because the black cat would feel warmer than the white one. The discrimination would then be based on a correlation: cats that absorb the most infrared radiation (heat) are also those that tend to absorb the most visible radiation, so hot cats also tend to be black. If the light reflected from objects is restricted to the visible spectrum, there is no scientifically acceptable evidence that colors are discriminable by touch (see Makous, 1966; Kaiser, 1983).

3 According to Henderson (1970, p. 1.)

4 An article by Feinberg (1968) is the lead article in the September 1968 issue of Scientific American, devoted exclusively to light. The 11 articles in the issue have been republished, along with a number of additional articles from other issues of Scientific American, in Lasers and Light, with introductions by Arthur L. Schawlow (San Francisco: Freeman, 1969).

5 See, for example, the textbook by Strong (1958, p. 58). We will not give references for all of the physical concepts introduced in this chapter, all of which are treated in detail in standard texts. We have tried to eliminate most of the mathematics and to encourage visualization of optical concepts. As a result, our treatment is not entirely rigorous.

6 An integrating sphere is used in photometry to measure all of the light in a beam (for example, that passing through a filter that scatters light) or to mix two beams. If the inside of a sphere is painted white, light admitted through a small hole will be diffusely reflected many times and will appear to "light up" the sphere uniformly.

7 See Boynton (1974) for an elaboration of these ideas.

8 Dirac (1958, p. 9); also quoted in Scully and Sargent (1972).


10 See for example, Dicharn (1976, p. 404) or almost any other optics textbook.

11 Here and in the discussion to follow, fluorescence is ignored. Surfaces that exhibit this phenomenon are widely used these days in advertising displays, producing very vivid colors that seem to glow almost as if they are self-luminous and in detergents as whitening agents. Fluorescence occurs when light is absorbed by the surface and is then re-radiated at a longer wavelength. If this is to be regarded as reflected light, then clearly it is not inevitable that the wavelength of incident photons is preserved in reflection. Fluorescence usually plays a very minor role in object perception.

12 A nondirectional photocell is one that will react in the same way to any photon incident upon its receiving surface, whatever the angle at which it strikes that surface. Most detectors are directionally sensitive: photons incident perpendicular to the surface are more likely to register than those striking at a grazing angle. This is true of the cone photoreceptors of the human eye (the so-called Stiles-Crawford effect).

13 A square degree of visual angle would result, for example, from the viewing of a square that subtends one linear degree of visual angle on each side. It could also be produced by a circular spot having a diameter of (2/√π) = 1.128°. One square degree is also equivalent to 3.046 x 10⁴ steradians.

14 According to Kingslake (1974, p. 799), Snell’s use of the word “image” to describe the intersection of ray paths and construction lines is not at all in accord with modern usage.

15 Descartes gave Snell no credit and was later accused of plagiarism. It is, however, entirely possible that Descartes arrived at "Snell's law" independently.

16 The prevailing view held that the speed of light was infinite. Newton thought it finite but predicted incorrectly from his corpuscular theory that light should travel faster in glass than in air.

17 Typically, only three wavelengths in the visible spectrum are corrected and some deviation of the others is allowed.