Introduction

I see trees of green, red roses too,
I see them bloom for me and you,
and I think to myself
What a wonderful world.

I see skies of blue and clouds of white,
the bright blessed day, the dark sacred night,
and I think to myself
What a wonderful world.

The colors of the rainbow, so pretty in the sky
are also on the faces of the people goin' by . . . . *

Explanation of the various effects of *light* is a very elusive task. Although light has captured the imagination of human beings since the dawn of civilization, science has yet to deliver a single, comprehensive explanation of all its effects. The advanced theories that now exist create many new questions along with new answers. Part of the confusion can be blamed on our tendency to explain physical phenomena using the perception of our senses. Unfortunately, our senses do not tell the full story. Although we can see light, and even distinguish among some of its colors, we cannot see most of the radiation emitted by the sun. Even our ability to visually determine the brightness of light sources is limited by the rapid saturation of the eye retina. Our senses tell us that light propagates in straight lines, yet careful experiments have demonstrated that the trajectories of light can be bent by gravitation. We cannot even capture and store light. We may observe that light propagates from a source until it is trapped by a target, but it does not seem to require any medium to carry it. We can demonstrate that the behavior of light is wavelike, but we also have sufficient evidence to indicate that it is made of particles that cannot be split. Although we know that these particles of light have momentum, they do not have any mass when at rest. Furthermore, although these momentum-carrying particles travel faster than any other particle, some cannot penetrate glass whereas others can penetrate metals.

* From "What a Wonderful World" by George David Weiss and Bob Thiele, © 1967 (Renewed) Quartet Music, Inc. & Range Road Music. All rights reserved. Used by permission.

To most people, light is simply what makes vision possible. However, on a bright day we can sense sunlight by its warmth on our skin even when our eyes are closed. We also know that the visual capabilities of animals and insects are different from ours. Therefore, to them light is not the same as it is to us. Evidently, the perception afforded by our eyes is insufficient to understand the nature of light. Contributions by celebrated physicists such as Archimedes, Newton, Maxwell, and Einstein helped us to develop theories that explain most of our observations. Using these theories, we have learned how to construct many of our modern devices. Theories formulated by Archimedes are still used to calculate simple focusing mirrors, and theories derived by Einstein were required before the first laser could be constructed.

Despite the advances of modern technology, many of the mysteries of light remain unresolved. Historically, new interpretations of the physical nature of light not only helped us to augment our understanding but also led to new technical applications. The most dramatic leap occurred at the turn of this century, when the theories of relativity and quantum mechanics emerged. Many of the applications discussed in this book could not be developed before these theories were understood. Today it is hard to imagine that many of the interpretations of the nature of light were not known even 100 years ago. However, despite the apparent progress, we still do not have one universal description of the nature of light. Instead, we have created several theories, each explaining only some of the effects while failing to describe others. As with many other engineering theories, the strength of this approach is that we can use these theories to design and build applicable devices, which operate as predicted as long as their range of application does not exceed the assumptions made by the theory. Thus, lenses and imaging devices may be designed by relatively simple geometrical optics techniques. If an evaluation of the chromatic correction for a lens is required, some aspects of physical optics must be introduced. To estimate the attenuation of imaged radiation due to absorption by some of the optical elements (e.g. filters), or to evaluate the emission by some light sources, quantum mechanical concepts may need to be used.

Any design in which optics or lasers are an integral part requires consideration of some of the theories of optics and radiation. Although these theories were traditionally part of other disciplines, the advent of modern applications has eliminated this artificial distinction. This book is an attempt to bridge the gap that may still exist between purely physical concepts and engineering applications. For simplicity, the text is structured along the lines of major theories of light and of radiation. The simplest theory, geometrical optics, is thus presented first, followed by physical optics and then theories about the interaction of radiation with matter.

1 Radiometry

1.1 Introduction

In the introduction we saw that explaining the concept of light may require more than just one theory. However, before we begin our journey through the disciplines of optics, we must identify the physical parameters needed to quantify the phenomena that are associated with light. But even before that, we should recognize that the phenomenon we call light is only a part of the broader phenomenon of radiation. If we consider radiation to be

the emission and/or propagation of energy through space in the form of electromagnetic waves or indivisible energy quanta,

then light may be defined (American National Standard 1986) as

the part of radiation that is spectrally detectable by the eye.

(This definition is sometimes extended to include ultraviolet and infrared radiation.) Note that, by the present definition, radiation that is spectrally detectable to the eye will be called light even if it is too faint to be seen. Although these definitions include terms (such as electromagnetic waves and spectra) that are yet to be explained, it is evident that light represents a subcategory of radiation. Thus, once the physical quantities that specify radiation are defined they may also be used for the quantification of light. Furthermore, the measurement of radiation – or *radiometry* – does not depend on how we define what is detectable by the eye. Therefore, radiometry is more objective than *photometry,* which is the process of measuring light. The quantities obtained by radiometry are sufficient for most engineering applications. Photometry is used primarily in technology associated with vision, which includes specifications of computer monitors, photographic films, color mixing, and lighting. These topics are beyond the scope of this book. (See American National Standards 1986 for nomenclature and definitions of photometry terms.) In the sections that follow we will discuss the radiometry terms to be used in this book.

The definition of radiation (see e.g. Edwards 1989 and Roberts 1991) suggests that radiometry must include: measurements of the energy that is transferred; the properties of the waves that carry it, such as wavelength or frequency; and the properties of the energy quanta, which are called photons. Since the properties of photons can be specified using properties of the electromagnetic waves, the list of parameters required for radiometry can be somewhat reduced. Using the American National Standard (1986), we will define parameters that specify the rate of transfer of the radiative energy, and will separately describe the characteristics of the electromagnetic wave that carries that energy.

1.2 Energy Transfer by Radiation

The primary effect of radiation is to transfer energy from a source to a target. However, since radiation can neither be stored nor brought to rest, a more natural parameter to consider is the *radiant flux* Φ, which is the time rate of flow of radiant energy. Using SI units, this flux is given in watts. As an example, the flux of the sun in Figure 1.1(a) is the rate at which all the emitted energy crosses an imaginary envelope marked by the dashed circle. Clearly, that flux is independent of the radius of the imaginary envelope. Of course, we do not expect to capture all the sun's energy. Therefore, an alternative measure of the radiation emitted by the sun will be the exitance $M(x)$ of a point x on the sun; see Figure 1.1(b). *Exitance* is the total radiant flux $\Phi(x)$ leaving an area element dA_S at point x on the source:

$$M(x) = \frac{d\Phi(x)}{dA_S} \text{ W/m}^2. \tag{1.1}$$

Previous definitions distinguished between emittance, or radiation emitted *by* the source, and exitance, which includes all radiation (e.g. reflection and transmission) emerging from a surface. The present American National Standard defines only the term exitance. For measurements of the exitance, all rays that emerge from a surface must be included. Technically this task may prove to be impossible. However, the exitance can sometimes be inferred from other measurements such as the source color or temperature.

After emerging from the source, radiation may propagate indefinitely until it encounters a scattering source or a target. There is very little interest in quantifying radiation along its path, but quantifying it at the target is an essential part of the design of any optical device. Therefore, parameters that are specific to the point of incidence must be defined. For example, the design of a planar solar collector requires that the power that falls on an area element from all possible directions be specified. This parameter, the irradiance, is similar to the exitance, except that its measurement includes radiation that is approaching the surface from all possible directions. Therefore, the *irradiance* $E(x)$ is defined as the total radiation energy from all possible directions that falls per unit time on a unit area A_T at point x:

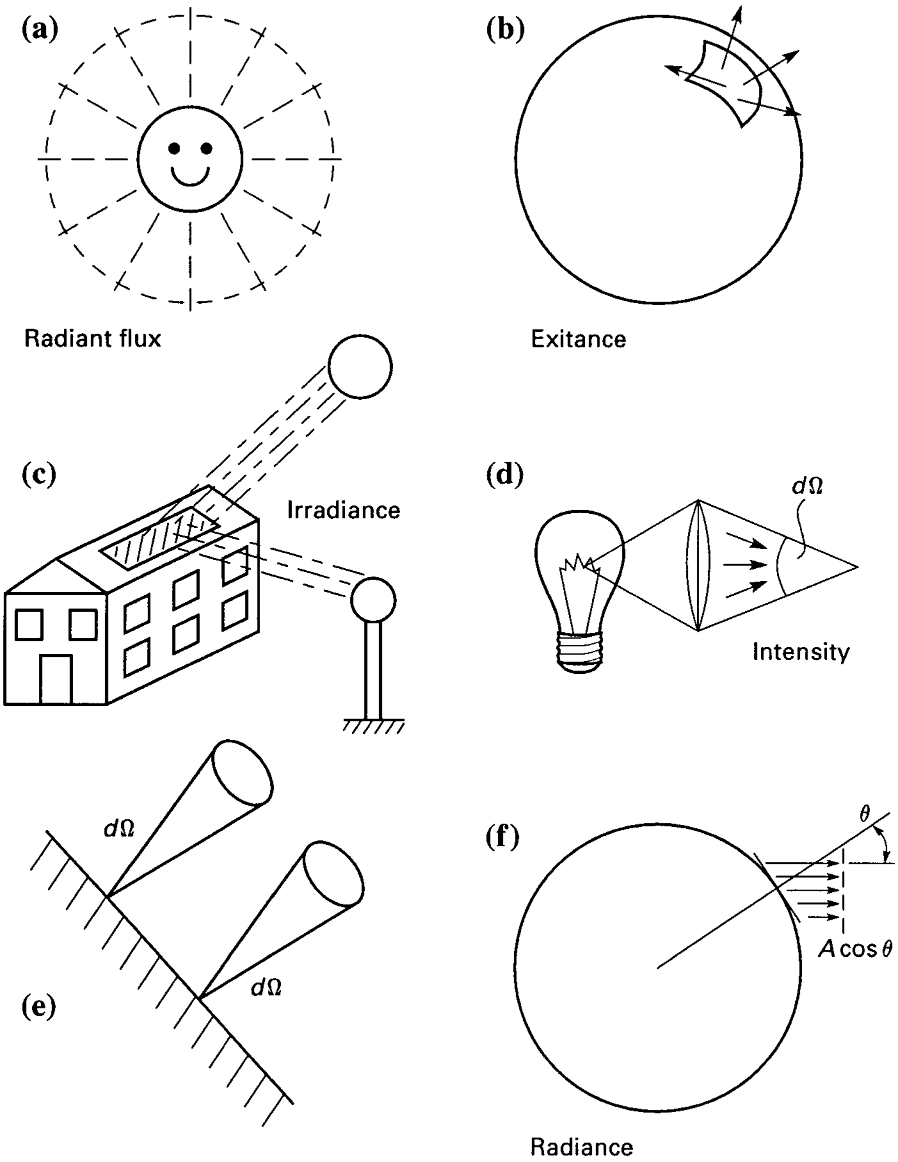

Figure 1.1 Modes of radiative energy transfer.

$$E(x) = \frac{d\Phi(x)}{dA_T} \text{ W/m}^2. \tag{1.2}$$

When more than one source is present, as in Figure 1.1(c), evaluation of the irradiance requires that radiation from all sources be included.

The design of telescopes or lenses requires that the power captured by these devices be specified. When the source is near the imaging device, as in Figure 1.1(d), the captured radiative power increases with the collection solid angle Ω. To determine the power collected by this lens, the intensity $I(\theta)$ must be specified. The *intensity* is defined as the total radiation emitted by the source, per unit time, along a line in the θ direction and within a solid angle $d\Omega$:

$$I(\theta) = \frac{d\Phi(\theta)}{d\Omega} \text{ W/sr.} \tag{1.3}$$

If uninterrupted, all the radiation power that is included within a solid angle Ω will be captured by an optical device with the same or larger collection angle. Note that mathematically a solid angle must have an apex and so the definition of intensity may strictly apply only to point sources. However, in reality a lens (or a telescope) can image a finite area of the source. Therefore, if the size of the imaged source is negligible relative to the distance, the intensity may include all the small cones that are oriented in the θ direction as in Figure 1.1(e) and that have a solid angle of $d\Omega$.

When the distance between an imaging device and a source increases, so that the collection solid angle Ω is approaching the infinitesimal limit $d\Omega$, all rays that are collected by the lens are almost parallel to each other. This is always true in astronomical applications. If the plane of the lens is perpendicular to these rays then the total radiation power captured by the lens can be defined by the radiance $L(x,\theta)$. The radiance is defined as the portion of the radiative flux that is contained within a cone with a solid angle $d\Omega$ pointing in a direction θ and crossing an area element that is projected normal to the direction of propagation; see Figure 1.1(f). Mathematically, this may be written as

$$L(x,\theta) = \frac{\partial^2\Phi(x,\theta)}{\partial\Omega\,\partial A(x)\cos\theta} = \frac{\partial I(x,\theta)}{\partial A(x)\cos\theta} \text{ W/sr-m}^2. \tag{1.4}$$

This definition does not distinguish between the radiation leaving a source or radiation incident upon a target. Therefore, the term ∂A in (1.4) represents an area element on an imaginary envelope either surrounding the source or attached to it. With this definition, the target area (e.g. collection lens) is normal to the incident rays, and the radiance specifies the power per unit area that falls on that target or lens.

1.3 Spectral Parameters of Radiation

In the previous section we discussed the terminology and units that are needed to describe the energy transferred by radiation. The wave or corpuscular nature of light were not part of these definitions because all the energy carried by the radiation was considered. However, in many applications the composition of the radiation must be defined as well. If we assume that radiation consists of electromagnetic waves that can be described by the sinusoidal waves shown in Figure 1.2, then the wavelength λ can be used to uniquely specify a certain wave. Although wavelength could be defined as the distance traveled by a wave between two points with the same phase, such a definition would not be complete because the wavelength can vary while the wave is traveling through media other than free space. Therefore, we define the *wavelength* as

the physical distance covered in free space by one cycle of that sinusoidal wave.

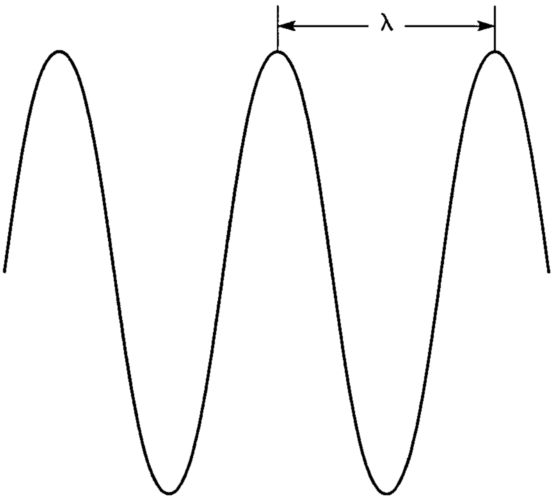

Figure 1.2 Wavelength of an electromagnetic wave.

This definition specifies explicitly that the measurement of the wavelength must be made in free space. Although wavelength measurements obtained in atmospheric air are sufficiently accurate for most applications, some tables list the results of wavelength measurements in vacuum (see Weast and Astle 1980). Included in these tables are the wavelengths of the radiation emitted by such sources as cesium, sodium, and mercury lamps. These lamps emit several monochromatic lines that can be used for the calibration of detectors or spectrum analyzing devices. Owing to their high efficiency, sodium and mercury lamps are also used for highway and street lighting.

The range of wavelengths that make up the radiative spectrum is unlimited. However, this infinitely wide spectrum can be naturally divided into sections in which the electromagnetic waves have comparable wavelength and all share some characteristic behavior or applications. Figure 1.3 presents the division of the radiative spectrum into such groups. The group of the shortest of wavelengths belongs to γ-rays, where $\lambda \approx 10^{-10}$ m. The longest waves on this chart belong to radio and microwave radiation, where λ ranges from 1 mm to hundreds of meters. The visible spectrum, marked by the shaded area, is seen to occupy a very narrow range.

Because of the large variation in wavelengths, the *units* for λ depend on where along the λ axis in Figure 1.3 the measurement is made. In this text we will be concerned primarily with the visible spectrum, where λ is specified in nanometers: 1 nm $= 10^{-9}$ m. For example, the nominal wavelength of a red He–Ne laser beam is $\lambda_{\text{He-Ne}} = 632.8$ nm. In textbooks the visible spectrum is sometimes specified in units of Angstroms (1 Å $= 10^{-10}$ m). The infrared spectrum is usually specified in units of micrometers (or *microns*), where 1 μm $=$ 10^{-6} m. For example, the nominal wavelength of a CO_2 laser beam is $\lambda_{CO_2} =$ 10.6 μm. Microwaves and radio waves are normally specified in millimeters and meters, respectively.

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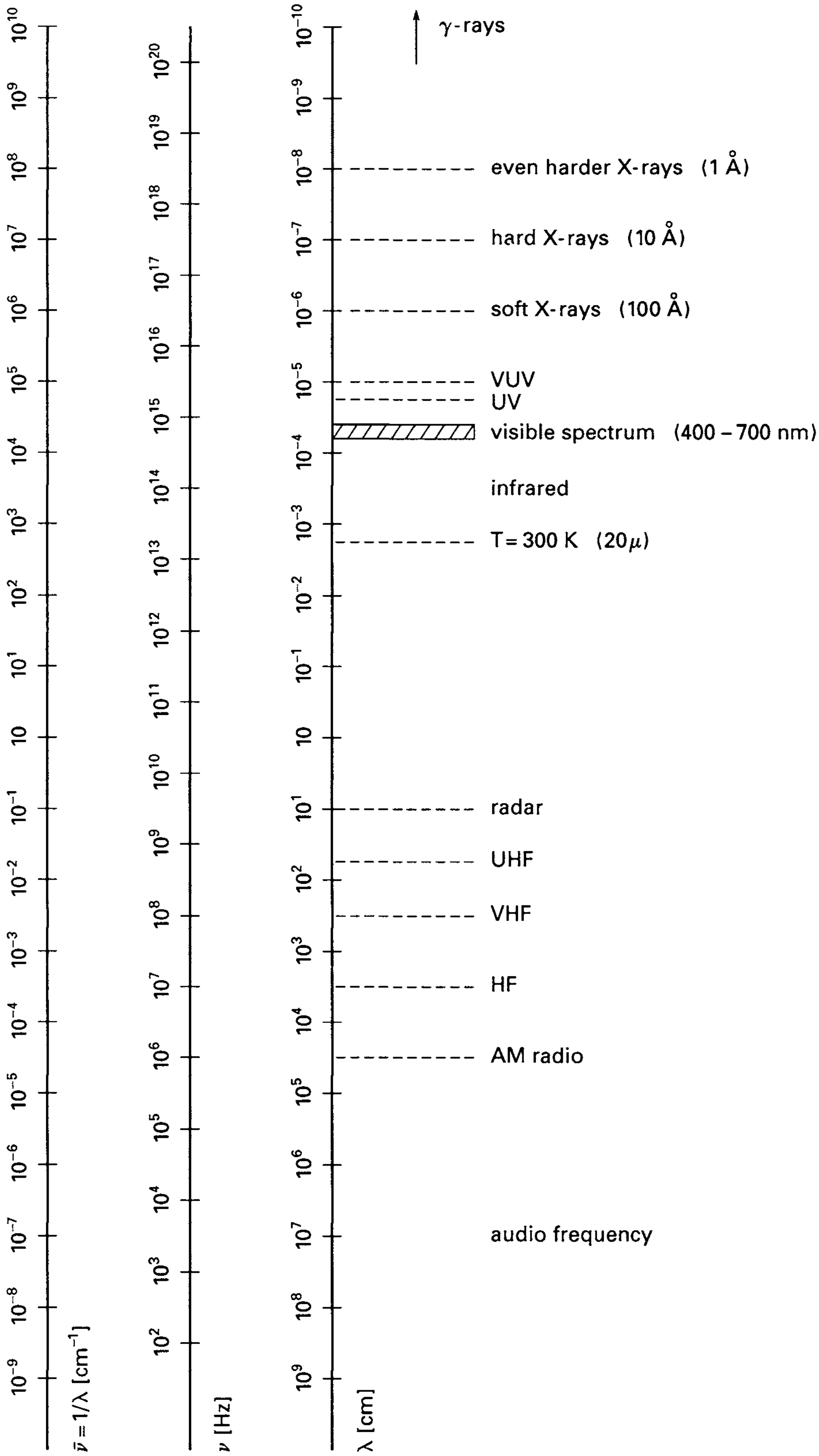

Figure 1.3 Division of the radiative spectrum into its spectral groups.

An alternative way to specify the spectral properties of radiation is by its frequency ν. Since the frequency and wavelength of radiation are related by the speed of light, specifying either the wavelength or the frequency is usually sufficient. The frequency of electromagnetic waves is defined in units of hertz [Hz] as the number of cycles completed by the wave in a second. Unlike the wavelength, the frequency of an electromagnetic wave is independent of the medium in which it travels. This, of course, presents an advantage because the same parameter applies to all media.

The frequency of electromagnetic waves in the visible spectrum approaches 10^{15} Hz. Since the frequency varies inversely with wavelength, the higher frequencies belong to the shorter wavelengths and the low frequencies represent radio waves and microwaves.

In most engineering applications, five significant figures are required to accurately specify the frequency. Since the frequencies of the visible, infrared, and ultraviolet spectra carry a high exponent, a new unit in which this high exponent is eliminated would be useful. Dividing the radiation frequency [in Hz] by the speed of light in free space ($c_0 = 2.9979 \times 10^{10}$ cm/s) yields a new representation of the frequency, $\bar{\nu}$, in wavenumbers [cm^{-1}]. For example, the frequency of the radiation of a red He–Ne laser beam is approximately $\nu = 4.74 \times 10^{14}$ Hz or $\bar{\nu} = 15{,}802.8$ cm^{-1}.

1.4 Spectral Energy Transfer

The terms presented in Section 1.2 are useful for the description of the total energy transfer. In order to evaluate these terms, all the spectral components of the radiation (either emitted or collected) must be included. However, most optical applications are concerned with radiation within a limited spectral range. Thus, application may include considerations of the total energy transferred through an optical filter that is transparent only to ultraviolet radiation. Furthermore, most filters may transmit different portions of the incident radiation at different wavelengths. Alternatively, atmospheric applications may require specification of the solar energy transmitted through the ozone layer. For these applications, new terms must be used. As a rule, all the terms described in Section 1.2 can now be redefined per unit wavelength. Thus the *spectral flux* Φ_λ is defined as the radiant flux per unit wavelength interval at wavelength λ:

$$\Phi_\lambda = \frac{d\Phi}{d\lambda} \text{ W/nm.} \tag{1.5}$$

The *spectral excitance* $M_\lambda(x)$ and *spectral irradiance* $E_\lambda(x)$ are similarly defined as the exitance and irradiance per unit wavelength at wavelength λ. The *spectral intensity* $I_\lambda(\theta)$ is the intensity per unit wavelength at the wavelength λ, and the *spectral radiance* $L_\lambda(x,\theta)$ is the radiance per unit wavelength at wavelength λ.

Other parameters and units may be used for the description of radiation. However, for most engineering applications, the terms described here will be sufficient. In the next chapters we will have more opportunities to familiarize ourselves with these concepts and their importance.

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