40 LIGHTING AND APPLICATIONS

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40.1 GLOSSARY

Illuminance. Luminous flux incident on a surface per unit projected area in the direction of emission relative to the surface normal. 1 lux = 1 lumen/m^2.

Intensity. Luminous flux emitted by a source per unit solid angle in a given direction. 1 candela = 1 lumen/steradian.

Luminance. Luminous flux emitted in a given direction per unit solid angle per unit projected area in the direction of emission relative to the surface normal. 1 nit = 1 lumen/(m^2 × steradian).

Luminaire. Lamp or lighting fixture that includes optical components, baffles, housing, and electronics.

Display. It refers to many things: a computer monitor, a projected image, and a piece of art or a decorative item.

Backlighting. It refers to illumination of an object from behind. The object can be opaque, translucent, or transparent. The light source is usually large in size and diffuse.

40.2 INTRODUCTION

Lighting is an area of science that includes the interaction between light and people in their daily lives. The primary goals of lighting are to provide the illumination to perform tasks, direct people to desired locations and provide a sense of security. Additionally, lighting has a profound effect on mood and sleep-wake cycles of all living beings. As mankind has advanced technologically, the needs fulfilled by lighting have also increased to additionally provide relaxation, alter moods, attract people, provide entertainment, create virtual environments and improve human productivity.

Unlike most of other fields in optics, lighting is a more subjective field than objective—it is based on the emission aspects and how it is perceived within its surroundings. The subjective nature is based upon our interactions with lighting shaped by vision biology and brain perception. The capabilities of the human eye largely determine the detectable range and variations (in both time and space) in colors and brightness. Perception depends upon the brain's interpretation of the input from the eye and is influenced by past experiences. For example, although brightness and the color of lit objects are mathematically represented by luminance metrics as a function of distance, direction and wavelength, the perception of these quantities is context dependent based upon the observer's experiences and environment. Thus, the same illumination levels in two different environments can be perceived as two drastically different lighting outcomes.

The importance of understanding lighting goes beyond the basic need to illuminate objects or surroundings. The importance of representing lighting accurately has been exemplified in art over the centuries.[1] Understanding lighting in the context of human perception and the ability to represent and simulate lighting on computers has attracted attention in fields such as virtual reality for training especially in the fields of medicine, aviation and computer-aided design, and entertainment such as video games and movies. As our understanding and computational capabilities have increased over time, so has the sophistication and quality of virtual environments and the entertainment media.

An effective lighting design is contextual, cultural and is well integrated into its surroundings. Light interacts intimately with everything it impinges upon. Every object, including humans, plants and architectural elements, has distinct scatter, reflective, transmissive, and absorptive properties that are dependent upon wavelength and direction of light. As a result, the lit objects contribute to the appearance of the scene. Lighting therefore must complement in concert with the architecture and its surroundings in form, composition, and style to meet our expectations for the lit environment. For example, our expectations for the lighting environment of a casino are quite different to that of a sports stadium, a retail store, an office or a hospital. In each case, there is a distinct purpose that directs the layout of the light sources with respect to the objects. Therefore, the lighting must change in each case as dramatically as the differences between the contexts of lighting. If it does not, then responses to the lit environment are often not positive, typically making, for example, a poor work environment for an office, a lackluster sales venue for retail, or an uncomfortable room in someone's home. This subjectivity is the most difficult aspect of lighting design. After all, the success of any lighting scheme depends upon being able to meet the expectations of its users. Simply said, we know a good lighting design as soon as we see it, but it has limited quantifiable metrics.

The history of modern lighting traces its origin back to the advent of artificial light sources: the incandescent light bulb, more than a century ago. Currently there is a wide variety of sources to choose from: incandescent (includes halogen), discharge (fluorescent, high-intensity discharge, sodium vapor), lasers, electroluminescent (includes LEDs and OLEDs), and daylight. The choice of light source depends on operating characteristics, cost, efficiency, and safety. The luminaire optics play a critical role in shaping the light distribution from the source. Thus the choice of the source and luminaire optics is an integral part of the lighting design process.

Any lighting design must comply with the relevant government regulations for the specific purpose of lighting. For example, safety is critical in transportation lighting, so there are stringent regulations on the relative intensity distribution from street lights and automobile headlamps to minimize glare and achieve the desired visibility. There are increasing numbers of government mandates on using efficient sources in many countries, such as the banning of inefficient incandescent sources in favor of fluorescent and LED light sources. In addition to regulations, there are guidelines for best lighting practices in various situations. These guidelines are published by national and international committees such as CIE (Commission Internationale de l'Eclairage or The International Commission on Illumination), IESNA (Illumination Engineering Society of North America), SAE International (Society of Automotive Engineers), CIBSE (Chartered Institution of Building Services Engineers), and many others. These groups publish guidelines on many aspects of lighting in the interiors and exteriors of homes, offices, educational institutions, hospitals, entertainment facilities, malls, industrial complexes, sports stadiums, theatres, museum, streets, parks, transportation, and even underwater. The goals of these guidelines are to help, at a minimum, to create designs that are functional, efficient and provide safe and comfortable lighting. It is in the hands of the lighting designer to add to this mandated objective illumination to achieve the desired subjective lighting—in other words, the aesthetics.

In this chapter, we provide an introduction to many facets of lighting by touching upon the perceptual and biological factors that guide lighting design (Sec. 40.3), design elements and methods to create functional and aesthetically pleasing designs (Sec. 40.4), technology of sources and design of relevant optics (Sec. 40.5), and measurement of lighting conditions (Sec. 40.6). We end the chapter with application examples on interior and exterior lighting in Sec. 40.7. These sections provide comprehensive data on source selection and guidelines for best practices in general and in specific application areas such as lighting for offices, homes, healthcare, retail, and transportation. Although very important aspects of lighting engineering, we do not discuss electronic control mechanisms, maintenance, and commissioning of a lighting design due to limited space.

We make extensive use of terms used in Radiometry and Photometry. The reader is encouraged to refer to the chapters on various aspects of radiometry and photometry in Chaps. 34 to 39 in this volume.

40.3 VISION BIOLOGY AND PERCEPTION

The lighting design is guided by our understanding of perception and vision biology. In this section, we touch upon various aspects of biology of vision and perception.

Vision Biology

Biological aspects of human visual system response[2] that are parameterized and used in lighting design are visual acuity (resolution, vernier, recognition, and stereoscopic), color sensitivity, accommodation, field of view, and adaptability to color and brightness changes.

Once adapted, the human visual system response does not change appreciably with time. The human visual system responds to over eleven orders of magnitude of luminance. However, at any given instance, only 2 to 3 orders of magnitude are adapted to by the eye. It takes up to 60 minutes to fully adapt to lighting conditions. Light adaptation takes place via change in the eye pupil size that controls the amount of light entering the eye (2 mm to 8 mm), photochemical processes in the retinal cells and neural processes that respond to change in the luminance below 600 nits when cone cells have not fully bleached. Neural adaptation occurs quickly, within the first 200 ms, and allows us to adapt to 2 to 3 orders of magnitude of luminance fluctuation, such as in lit spaces of building interiors. Pupil adaptation via change in the pupil size takes up to few minutes and allows us to adapt up to 1 to 2 orders of magnitude of luminance fluctuation. For tasks that require good color discrimination, several minutes to an hour are needed for this color adaptation. The higher the luminance, the shorter is the adaptation time. Based upon luminance, three vision conditions exist:

1. Photopic vision occurs when bright illumination conditions in the visible (luminance >3 nits) exist. Both the rod and the cone cells in the retina are excited, but the rods are saturated and thus effectively ignored except for peripheral vision. Full color vision with highest resolution is possible. Most indoor lighting conditions ensure photopic enabling lighting conditions.
2. Scotopic vision occurs when low illumination level in the visible (luminance <0.001 nits) exists. Only the rod cells in the retina are excited. No color vision occurs and only low-resolution peripheral vision is possible. Lighting design is usually not done for the scotopic domain but it must take into account our peripheral vision capability wherever possible to help guide the individual toward relevant objects.
3. Mesopic vision is described by the transition between photopic and scotopic. The rod cells are excited and the cone cells are partially excited. The eye has limited color discrimination and resolution capabilities. Most outdoor artificial lighting conditions operate in this region.

The luminance and color distributions should be such that it includes individuals with impaired vision that cannot be corrected such as reduced illumination at the retina (50 percent for a 50-year old as compared to a 20-year old) due to smaller pupil size and reduced transmission efficiency of the eye, reduced contrast, increased glare sensitivity, loss of accommodation and reduced field of view caused by ageing, macular degeneration, cataract, or glaucoma. For most such cases increased illuminance, slow transients from the light to dark regions and an environment with reduced glare help considerably.[3]

Perception

It is the perception of lit environment that eventually determines the acceptability and adequateness of lighting conditions. Lighting perception is ultimately determined by the human visual system response and brain processes that are individual dependent. It is the latter that brings considerable subjectivity to lighting perception. Lighting design criteria for specific environments are often guided by studies that determine average perceptual responses. These guidelines are continually evolving, in response to geopolitical factors, research on vision biology and technology.

Depending upon an object's optical and physical characteristics and how it is viewed in relation to its surroundings, lighting can alter its perceived visual attributes. Visual attributes of physical objects are defined in terms of brightness, lightness, hue, saturation, transparency, and glossiness. We explain each of these attributes below and also show that not every object has each of these attributes.

Brightness is the perceptual correlate of luminance. Although, in the absence of a background, the perception of brightness of an object is proportional to its luminance in a logarithmic manner (log of brightness is proportional to log of luminance), the perception of brightness is dependent upon adaptation to the surroundings and the relative hue and saturation of the object. Figure 1 shows an example of how the brightness perception is altered by surroundings.[50] Different portions of a uniform luminance bar appear to have different brightness depending upon the local background. Similarly, car headlights appear much brighter in the dark than in daylight. Both vision biology and perception play a role here. Due to low ambient lighting, the pupil dilates and admits much more light (up to 16 times in night than in the day). Therefore, any bright source leads to sudden pupil contraction and ensuing discomfort. The sources appear even brighter due to a dark background, an effect similar to Fig. 1. Color perception is similarly affected. Color-saturated objects tend to appear brighter and vice versa.

Lightness is the perceptual correlate of diffuse reflectance. Our perception of an object being dark or light depends upon our estimate of its reflectance. For example, a piece of white paper appears white irrespective of the illumination falling upon it as we know from prior experience that it has a high reflectance. We tend to perceive it whiter than other objects of lesser reflectance even when the flux reflected by white paper in relatively low illumination is lower than a grey object that is placed under higher illumination. This confusion would not occur if we view a small region of the object through an aperture without knowing anything about the object. The aperture masks the contextual information and forces us to make objective judgments.

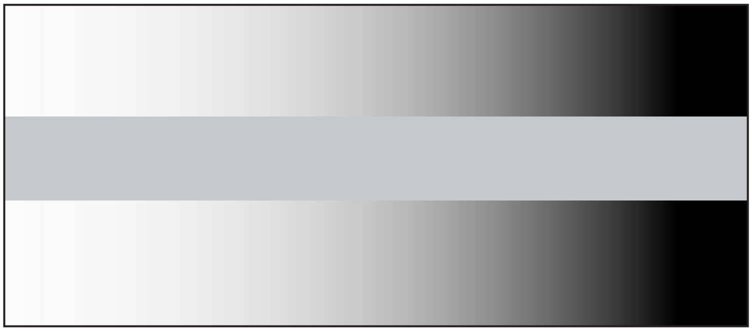


FIGURE 1 Perception of brightness. The rectangular bar in the center has constant luminance yet it seems brighter against a darker background at the right hand side.

Hue is the perception of dominant wavelength of the color spectrum transmitted or reflected by the object. It helps us judge if an object appears close to a known color such as red, blue, yellow, purple, green, colorless, or a combination of multiple colors such as bluish-green. Saturation is the perception of the extent of color purity. Highly saturated colors have a narrow band of wavelengths, centered on the hue. Transparency is the perception of the degree of light penetration into the object. Glossiness is the perception of smoothness of a surface relative to a matte finish.

Depending upon the properties of an object, the lighting conditions and how it is viewed, one or more visual attributes can be determined. For example, if an object is viewed through an aperture that hides the information of its surroundings or is illuminated such as nothing other than the object is visible then only attributes like brightness, hue, and saturation can be observed. A self-illuminated object or an object that gives the appearance of being so (such as a lit computer monitor) does not display lightness or glossiness, but if it stops emitting light, these attributes can be observed under external illumination.

Our brain attempts to maintain a perceptual constancy of shape, color, size, and lightness of lit objects based on past experiences and the context in which an object exists. Perceptual constancy allows us to maintain a certain perception of an object or a scene under changing viewing conditions. For example, we can recognize an apple as such when viewed at different angles, surroundings, or lit conditions. We can perceive a skyscraper as a tall building even if seen from far away and having a small image on the retina. Similarly, a tilted book appears rectangular although the image in the retina is trapezoidal. We can perceive the colors of common objects around us fairly correctly while wearing mildly colored glasses. Lighting can help maintain or alter perceptual constancies. To maintain perceptual constancies the lighting conditions must be such as there is adequate ambient lighting with high-color-rendering sources and without any disability glare. We discuss the terms such as color rendering, glare, and the impact of ambient lighting in the next section. The position of the light sources must be obvious to the observer even if not directly visible to establish the directionality of illumination. Direction of illumination is important as we tend to expect light to come from above and our perception of lit objects takes that into account at a subconscious level.

The relative distribution of light can impact the perception of the space itself and as such can impact human behavior.[4] For example, there is a general tendency among humans to be attracted to brighter regions of space. It can be demonstrated by viewing people that there is a clear trend toward walking on brighter areas of pathways or facing brightly illuminated areas of a restaurant. That is why brightly lit shopping malls are quite effective in attracting traffic as compared to a poorly lit shopping complex. The knowledge of human behavior toward lit space is also used in making more effective lit object displays and navigational aids. There are four distinct categories of light distribution[5] that affect the perception of space: privacy, relaxation, visual clarity, and spaciousness. An effect of privacy can be created by utilizing nonuniform high-brightness illumination across the vertical surfaces in the room with dark spaces in the occupant domains and low ambient luminance. An effect of relaxation can be created by using nonuniform warm (correlated color temperature (CCT) <3500 K) ambient light across the room. Visual clarity in the environment is emphasized with cool light (CCT >4000 K), high and uniform brightness near the center of the room and at all task planes. In addition, higher emphasis is given to ceiling and horizontal surfaces. A sense of spaciousness can be implemented with uniform room illumination and relatively higher levels of brightness on the walls and ceilings.

Summary

Understanding perception and biology of vision helps us develop models to describe desired lighting conditions. An example is the development of the relative visual performance (RVP) model. This model has been extensively developed by Mark Rea and his colleagues over the last few decades[6] to obtain the relative visual performance of a given task under different lighting conditions and establish lighting guidelines. RVP is provided as a probability of performing a visual task successfully under given lighting conditions. Task performance depends upon both visual and nonvisual aspects of the task. To obtain the true impact of lighting conditions on task performance, it is necessary to isolate those tasks for evaluation that are dominated by the visual component. The impact of the nonvisual components is minimized by quantifying their effect to the fullest possible extent and subtracting it from the overall task performance. A key finding of the RVP model is that the visual performance improves rapidly as the luminance contrast between the task and the background increases up to 40 percent. Beyond this value, the improvement in visual performance is negligible with increase in contrast. Luminance contrast in this context is defined as

$$\text{Luminance contrast} = 100(L_{\text{Task}} - L_{\text{background}})/L_{\text{background}} \tag{1}$$

Visual performance curves (performance metric versus luminance contrast) can be evaluated for various task sizes and background luminance. A major limitation of the existing RVP model is its limited validity to only those tasks that are quantifiable by task size, luminance contrast, and background luminance and only under the conditions of foveal vision. We need more sophisticated task performance models to cover a larger range of tasks.

In the sections to follow, design guidelines make use of the understanding of lighting perception and vision biology to justify their development.

40.4 THE SCIENCE OF LIGHTING DESIGN

The lighting design process begins with identifying the needs to be addressed. An understanding of the functions of lighting and knowledge of basic building blocks helps us in making a preliminary design. The quality of lighting is determined by its ability to fulfill human needs in an economical and environmental friendly manner while at the same time complementing the architecture in form, composition, style, codes, and standards. We discuss the lighting design process in the following subsections:

Design considerations. We discuss the factors involved in creating a lighting environment for an application. The categories discussed are: goals, context, illuminance, color, visual discomfort, trespass and light induced damage of objects.

Functions of lighting. Here we discuss the four primary functions of lighting: ambient, task, decorative and accent.

Lighting geometries to achieve specific functions of lighting. Here we discuss the building blocks for lighting design.

Properties of objects and their impact on lit scene are discussed.

Modeling. Here we discuss the techniques used to simulate a lit environment in order to achieve the best design.

Design Considerations

Goals Lighting for any application must take into account the needs (both human and nonhuman such as plants or animals), lighting economics, environment impact, and architectural aspects of the application. Human needs include the desired degree of visibility, comfort, ability to perform the needed tasks, social communication, ambience, and aesthetics.

Context Lighting helps create a perceptual environment or ambience to suit a specific application such as office, home, lobby, restaurant, casino, or a sports stadium. Appropriate selection of lighting schemes and luminaires that complement the architecture and interior design helps in achieving the desired ambience.

TABLE 1 IESNA Guidelines on Illumination Categories and Average Illuminance Levels

Category	Average Illuminance (lx)
Public spaces	30
Simple orientation or short visits in a new environment	50
Working spaces where simple visual tasks are performed	100
Performance of visual tasks of high contrast and large size	300
Performance of visual tasks of high contrast and small size, or visual tasks of low contrast and large size	500
Performance of visual tasks of low contrast and small size	1,000
Performance of visual tasks near vision threshold	3,000–10,000

Large size: Object's projected solid angle subtense at the eye $>4.0 \times 10^{-6}$ sr.
Small size: Object's projected solid angle subtense at the eye $\leq 4.0 \times 10^{-6}$ sr but not near the visual acuity limit.
Low contrast: ≤ 0.3 but greater than visual threshold.
High contrast: >0.3.

Illuminance—Horizontal and Vertical Horizontal and vertical illuminances refer to illuminance distribution on horizontal and vertical planes respectively. Table 1 describes IESNA guidelines on illumination categories and average illuminance levels needed for each.[7] These guidelines do not apply to special situations that involve setting up a particular ambience or focusing on an object for emphasis.

The uniformity of luminance/illuminance is generally defined by the ratio of maximum to minimum luminance/illuminance. The need for uniformity across the field of view and across the entire space depends upon the application. The human eye is a brightness detector and is thus responsive to changes in luminance. To calculate luminance, illuminance, and the reflectivity of surfaces must be taken into account. For Lambertian surfaces (surfaces of constant luminance, independent of the viewing direction),

$$\text{Luminance} = (\text{illuminance} \times \text{ surface reflectivity})/\pi \tag{2}$$

Generally, a luminance uniformity of 0.7 within the field of view across the task is considered adequate as the eye is unable to detect these variations. Not all tasks require high luminance uniformity. For example, in tasks involving inspection of 3D objects, nonuniform illumination is able to highlight the geometrical features, especially surface textures much better due to being able to provide better depth perception. In lit environments, a nonuniform light distribution is used to provide perceptions of privacy or exclusivity, for example in retail lighting or in restaurants. A luminance ratio (maximum luminance: minimum luminance) of greater than 15:1 is generally considered undesirable. In the applications section, we discuss the recommended luminance ratios for several scenarios in a variety of applications.

Color Lighting influences the color appearance of lit objects. For most lighting applications, white light is the standard form of illumination: exteriors (landscape, roadways, buildings, city, and stadiums) and interiors (homes, offices, restaurants, museums, industrial complexes, and shopping malls). Saturated colors in lighting are used only in special applications like indicators or signals, displays, color-specific industrial applications such as those involving color discrimination, special effects in casinos, hotels, malls, or discotheques, and so forth. The chapter on colorimetry in this *Handbook* (Vol. III, Chap. 10) provides an excellent introduction to the subject of color.

Depending upon needs such as aesthetics, task performance, and color-dependent reflective properties of objects, an appropriate light spectrum must be selected. The desired light spectrum can be achieved by using light sources that emit in that spectrum, by using static filters on the sources to tailor the spectrum or by spatial and time-averaged color mixing. Spatial color mixing involves using multiple light sources that emit in different portions of the desired spectrum but are laid out in such a manner that the lit environment or object appear to be illuminated by light having the combined spectrum of individual light sources. Time-averaged color mixing involves high-frequency (>60 Hz) mixing of different portions of the light spectrum in different proportions. If the frequency of color mixing is high enough, the brain perceives a specific color based on the time average of the varying spectra used in their respective strengths. For example, in modern digital projectors, a color wheel is used that has various segments of different spectral transmission. When it rotates through those segments, one can create the appearance of any color within the color gamut of the light source. In the section on LEDs, we discuss color mixing to create white light or any desired color. Spatial and temporal color mixing can be used together to create a variety of effects. Although color mixing can achieve the visual perception of any desired color in emission, its ability to color render the object it illuminates depends upon the product of incident light spectrum and wavelength-dependent reflectance of the object. In this section we discuss how white light is specified and how its ability to render objects is estimated.

It is tedious to choose light sources if we have to analyze the spectrum and its impact on common objects. For white light, the color rendering index (CRI) and the correlated color temperature (CCT) help provide a quick estimate of the appearance of light and its color rendering of lit objects. For example, at a CCT of 2700 to 6500 K, a CRI ≥70 is adequate for common situations such as in offices and homes, a CRI ≥50 is sufficient for most industrial tasks and a CRI ≥90 is needed for stringent color discrimination tasks such as hospital surgery, paint mixing, or color matching. In the future, it is likely that different metrics based on color-appearance models would be in use. This is especially true with the increasing use and availability of a variety of light sources, especially LEDs, which have significantly different emission spectra from incandescent sources.

The CCT is the temperature of the planckian (perfect blackbody) radiator in Kelvin whose perceived color most closely resembles that of a given stimulus at the same brightness and under specified viewing conditions.[8] To find the CCT, the nearest point on the planckian locus is considered but only in a perceptually uniform color space. The isotherms across the planckian locus in a uniform color space are represented as normal to locus curve but in a nonuniform color space such as XYZ, these are no longer perpendicular to the locus.

Color rendering is defined as the effect of an illuminant on the color appearance of objects by conscious or subconscious comparison with their color appearance under a reference illuminant.[8] Two functional reference illuminants are currently used for calculating CRI: (1) for a source CCT up to 5000 K, a blackbody at the same color temperature is used and (2) for a source CCT above 5000 K, one of the phases of daylight is used. The phase of daylight selected is such that its chromaticity is within 1/(15E6 K) to that of the test source. It is defined by a mathematical formula based on the CCT of the test source.[9] For all cases, a CRI value of 100 is considered to be a perfect match between the test source and the illuminant. The precise steps and calculations needed to calculate the CRI are recommended by the CIE.[10] Here we summarize the results:

$$\mathrm{CRI}(R_a) = 100 - 4.6\overline{E}_{\mathrm{UVW}} \tag{3}$$

where R_a refers to the general CRI and $\overline{E}_{\mathrm{UVW}}$ is the average of the Euclidean distances between the color coordinates of the reflected reference and test light sources from the first 8 out of the 14 CIE-prescribed test samples (see Ref. 10). The color coordinates of the test source are chromatically adapted to the reference source and are expressed in the CIE 1964 color space. The CRI calculation is valid only when the color difference between the test source and the reference source is not large.

Although CRI is a useful metric and is widely used, it has several shortcomings. The existing method of calculating CRI is not perceptually well correlated. The high CRI predicted for sources with extreme CCT do not have good color-rendering properties. CRI is not valid for sources such as discrete spectral LEDs where CCT cannot be defined. CRI cannot be used to evaluate white-light LEDs with nonuniform spectra; the CRI predicted is quite low although the quality of white light appears to be better. The practice of using only eight test samples, none of which are saturated creates situations where high CRI sources do not color render color-saturated objects correctly. The CRI formulation can be modified to include the impact of different reference illuminants for different source types, color spaces, test sample set, different chromatic adaptation formulas or even a reduced focus on absolute color fidelity. CIE reviews various propositions in this regard and updates its recommendations.

Visual Discomfort Visual discomfort can be caused by a variety of reasons.[11] Many of these reasons are context dependent where the expectation of the nature of lit environment determines the suitability of lighting. It also depends on cultural differences between various groups of people. For example, lighting flicker in a dance club may be desirable as opposed to almost all other situations. Similarly, the preference of color among different cultural groups varies considerably. Visual discomfort occurs when lighting creates perceptual confusion. For example, if the pattern of illumination is such that surfaces of higher reflectance reflect less light than the surfaces of lower reflectance, perceptual confusion may result. The causes of visual discomfort that are more specific to lighting are summarized as follows:

Insufficient lighting Insufficient lighting, especially for task performance, results in eye strain besides reduced task performance. For different tasks, there are different levels of horizontal and vertical illuminance necessary to be considered adequate. Table 1 describes suggested horizontal illuminance levels needed for certain situations. Lighting communities across the world have established guidelines for illuminance levels for a wide variety of specific tasks and environments.

Uniformity Visual discomfort occurs when the uniformity across the field of view is not as expected. A high uniformity can be as undesirable as a high degree of nonuniformity especially when considered across the entire visual field of view. Both can cause severe eye strain. In the section on applications, we provide examples of preferred luminance ratios between task and its vicinity.

Glare Glare results when there are regions of unexpected very high levels of luminance in the field of view. Glare can be direct or indirect. Direct glare occurs when a light source or a portion of it visible such as in overhead lamps, automobile headlights, or direct sunlight. Indirect glare occurs when the light is reflected or scattered directly into the eye, such as the sky reflecting off a lake surface and obscuring the view beneath the water surface. Glare comes in many forms:[12]

1. Flash blindness: This is caused by a sudden onset of bright light leading to temporary bleaching of retinal pigment.
2. Paralyzing glare: This is caused by sudden illumination with bright light that can temporarily "freeze" the movements of the observer.
3. Distracting glare: This is caused by flashing bright sources of light in the peripheral vision field.
4. Retinal damage: When the light is bright enough to cause retinal damage.
5. Saturation or dazzle: When a large portion of the vision field is dominated by bright source(s), which can be alleviated by wearing low transmittance eye glasses.
6. Adaptation: When one enters from a low ambient illumination region to a bright ambient illumination region without a transition region to help in vision adaptation.
7. Disability: This is caused by intraocular light scattering which reduces the luminance contrast [See Eq. (1)] of the task image at the retina. The impact is loss in task performance due to reduced visibility.
8. Discomfort: When the glare causes discomfort or distraction but does not affect the task visibility to the extent of limiting its performance

Note that several forms of glare can exist concurrently, especially discomfort with the other types. Discomfort and disability glare are the most commonly experienced glare forms. There are several mechanisms available to estimate the impact of these forms of glare. We discuss briefly the CIE-recommended models for disability and discomfort glare.

Disability glare Disability glare occurs when the luminance contrast [Eq. (1)] of the task image at the retina falls due to the superposition of intraocular scattered light on the retinal image.

This background noise from scattered light can be thought of as viewing through a veil. Therefore, it makes sense to define an equivalent glare (or veiling) luminance (EVL) that mimics the impact of disability glare. The luminance contrast C is described as

$$C = \left| \frac{(L_b + L_{\mathrm{EVL}}) - (L_{\mathrm{object}} + L_{\mathrm{EVL}})}{(L_b + L_{\mathrm{EVL}})} \right| = \left| \frac{L_b - L_{\mathrm{object}}}{L_b + L_{\mathrm{EVL}}} \right| \tag{4}$$

where L is object luminance and b is background.

As the equivalent veiling luminance L_{EVL} increases, contrast at the retina C reduces. The contrast reduction is especially severe during difficult viewing conditions such as fog or nighttime when the object luminance is low. That is why car headlights are a much stronger glare source in the night than in the day.

Equivalent veiling luminance L_{EVL} is defined as:[13]

$$L_{\mathrm{EVL}} = \sum_i \left[\frac{10}{\theta_i^3} + \left\{ \frac{5}{\theta_i^2} + \frac{0.1p}{\theta_i} \right\} \cdot \left\{ 1 + \left(\frac{A}{62.5} \right)^4 \right\} + 0.0025p \right] \cdot E_i \tag{5}$$

where E_i = illuminance at the eye due to ith glare source
θ_i = angle of the glare source (in degrees) from the line of sight, $0.1° < \theta_i < 100°$
p = eye pigmentation factor (0 for black eyes, 0.5 for brown eyes, 1.0 for light eyes, and 1.2 for very light-blue eyes)
A = age of the viewer in years

For young adults (<35 years of age) and for glare source angle, $1° < \theta_i < 30°$, Eq. (5) approximates to

$$L_{\mathrm{EVL}} = \sum_i 10(E_i/\theta_i^2) \tag{6}$$

The EVL as described above is strictly due to intraocular scatter. In practice, it is necessary to add to this the luminance from external scatterers, such as fog or dust in the atmosphere, to yield the correct retinal contrast.

Equation (5) is currently the most sophisticated recommended treatment for disability glare. It can be applied toward a wide variety of circumstances, including indoor lighting, street lighting, and bright sky at a tunnel's exit.

For road lighting, the CIE recommendation on disability glare[14] is given by a percentage threshold increment (TI) described by Eq. (7). TI is limited between 10 and 15 percent.

$$TI = 65(L_{\mathrm{EVL}}/L^{0.8}) \tag{7}$$

where L_{EVL} = equivalent veiling luminance as described by Eq. (5)
L = average road surface luminance

Discomfort glare There are many formulations that describe discomfort glare. Each model is prescribed for well defined geometries and sources. Discomfort glare has been described by the visual comfort probability (VCP) model[15] in North America, British Glare Index system[16] (CIBSE) and the European glare limiting system.[17–19] Each of these systems has validity under specific constraints. Many luminaire manufacturers in North America and Europe provide VCP or glare index tables for worst case scenarios. CIE has proposed a Unified Glare Rating (UGR) model[20] to replace these systems. We describe here the formulation recommended by CIE.

The UGR formula is described by Eq. (8). UGR values range from 5 to 30, the higher values signifying a greater level of discomfort. For home and offices, UGR is specified at <20 and for industrial application it is >20. This formula is valid for source areas between 0.005 and 1.5 m^2. For smaller

TABLE 2 Glare Specification for Large Sources Such as an Illuminated Ceiling

Maximum Average Illuminance (lx)	UGR
300	13
600	16
1000	19
1600	22

sources, UGR overestimates the glare and for larger sources, UGR underestimates the glare. Therefore, for ranges outside the validity of UGR, CIE has provided detailed prescriptions to tackle small, large, and complex luminaires.[21] For source areas smaller than 0.005 m^2, Eq. (9*a*) is recommended. In practice, any bare incandescent lamp, frosted or clear qualifies as small. For source areas larger than 1.5 m^2, but not as large as an illuminated ceiling or uniform indirect lighting (see Section, "Lighting Geometries," for a definition of indirect lighting), UGR is modified into a large room glare rating (GGR) and is described by Eq. (9*b*). The same UGR and GGR values represent an identical level of discomfort. For very large sources, only the maximum average illuminance values correspond to a specific UGR rating, as shown in Table 2. For nonuniform indirect source, CIE has provided guidelines.[21] Each of the glare formulations discussed in this section are independent of the light spectrum.

Equations (9*a*) and (9*b*) are expressed for a single small and a single large source, respectively. Equation (9) is valid for viewing angles greater than 5° from the line of sight. For a combination of sources of different sizes, Eq. (8) must be modified to include glare from sources specified by equations (9*a*) and (9*b*).

$$\mathrm{UGR} = 8\log_{10}\left(\frac{0.25}{L_b}\right)\sum_i \frac{L_i^2\omega_i}{P_i^2} \tag{8}$$

$$\mathrm{UGR}_{\mathrm{SingleSmallSource}} = 8\log_{10}\left(\frac{0.25}{L_b}\right)\frac{200(I^2/R^2)}{P_i^2} \tag{9a}$$

$$\mathrm{GGR}_{\mathrm{SingleLargeSource}} = \mathrm{UGR} + \{1.18 - (0.18/\mathrm{CC})\}8\log[2.55\{1+(E_d/220)\}/\{1+(E_d/E_i)\}] \tag{9b}$$

where L_b = average luminance of the field of view without the luminaire or glare source
L_i = luminance of the *i*th luminaire in the observer's direction
ω_i = solid angle of the *i*th luminaire subtended at the observer's eye
P_i = Guth Position index[22] of the *i*th luminaire. [It is a function of angular deviations (vertical and horizontal) from the line of sight and valid up to 53° of deviation from the line of sight. See Eq. (10).]
I = luminous intensity of the small source expressed in lumens per steradians. The source must be >5° away from the line of sight
E_d = direct illuminance at the eye due to the source
E_i = indirect illuminance at the eye = πL_b
CC = ceiling coverage = (area projected by the source at nadir)/(area lit by the source)

$$P_i = \exp\{(35.2 - 0.31889\alpha - 1.22e^{-2\alpha/9})10^{-3}\beta + (21 + 0.26667\alpha - 0.002963\alpha^2)10^{-5}\beta^2\} \tag{10}$$

where α = angle of the plane containing the observer's line of sight and a line from the observer to the source from the vertical direction. [Vertical direction is the height above (orthogonal to) the floor on which the observer is positioned.]
β = angle between the observer's line of sight and the line from the observer to the source

For roadway lighting, the glare rating is affected by driver fatigue, vehicular speed, and whether the person in the car is driving or not. All these effects must be dealt with comprehensively to formulate a single glare rating model that is largely driver independent. There is ongoing research in this field to develop better models for evaluating glare for road and vehicular lighting.[23,24] Current CIE recommendation for limiting the discomfort glare for road lighting is identical to disability glare as described by Eq. (7).

Veiling reflections Veiling reflections are reflections from the task surface that result in the luminance contrast [Eq. (1)] reduction of the task itself. Veiling reflections can be evaluated from the source-task-eye geometry. It has been found that 90 percent of test subjects find a luminance contrast reduction of 25 percent as acceptable.[25] Veiling reflections are sometimes used as highlights to reveal the specular nature of a display (a lit object).

Miscellaneous Design Issues Other issues include designing against unacceptable light pollution or trespass, light-induced degradation or damage of objects and flicker from light sources. UV and IR filters are used with luminaires when there is a potential of damage to artwork or object displays. Flicker is more noticeable with high levels of the percentage modulation, area of visual field that is impacted by it, or the adaptation luminance. The impact of flicker can be reduced by using high frequency electronic ballasts or multiphase power supplies for different sources.

Functions of Lighting

There are four functions of lighting: ambient, task, decorative, and accent.[26] For each function, there are several implementation geometries. For most applications, more than one of these functions is necessary. We first discuss each of these lighting functions and then the lighting geometries used to accomplish these functions.

Ambient lighting fills up the space and is integral to almost any lighting scheme and yet is commonly ignored. It reduces the difference between the magnitudes of vertical and horizontal illuminance. As a result, it reduces glare, softens shadows, and provides a well-lit appearance. A common mistake is to consider any light that is illuminating the space as ambient light. For example, ceilings with recessed down lights with a narrow angular spread cause harsh shadows of objects on the ground. Even facial features show unflattering shadows. This is a result of insufficient level of vertical illuminance. So although there seems to be enough light to illuminate the space, it does not achieve a proper balance between vertical and horizontal illuminances resulting in cast shadows. To achieve proper ambient illumination, it is necessary to use those lighting geometries that spread light into large angles and from many directions. Ambient lighting is provided by large overhead luminaires with diffusers, torchieres, wall sconces, cove lighting, cornice lighting, valence and wall slot lighting, illuminated ceilings and wall washings. Figure 2 illustrates some of these schemes. Figure 4 illustrates ambient lighting with wall sconces.

Task lighting is used to provide sufficient illumination at the task plane such as a desk or work plane. Task lighting should be free of glare and shadows caused by the illuminated objects such as shadows from the hand and body or shadows from machine parts. Several lamp types and lighting geometries are available to reduce the impact of shadows. Lamps such as Banker or Bouillotte (Fig. 24) or large overhead luminaires with diffusers are good choices. The light emanating from these lamps is spread over a wide range of angles from an effectively large source. In a Banker lamp, a significant portion of light from the source undergoes multiple reflections from the inside of the luminaire before exiting. Large fluorescent light sources in a vertical configuration in the Bouillotte lamp provide excellent vertical and horizontal illuminance. Lamps with batwing lenses achieve cross illumination or lighting from two different directions overlapping in the task region. A batwing lens has a linear prism array (Fig. 23*c*) at the front of the source that leads to spreading of the light in predominantly two directions from each source point. Side lights installed in the vicinity of the task region increase vertical illuminance, and when used with overhead lighting provide excellent task lighting. Sometimes backlighting is necessary for certain tasks that involve transparent objects. Task lights must have

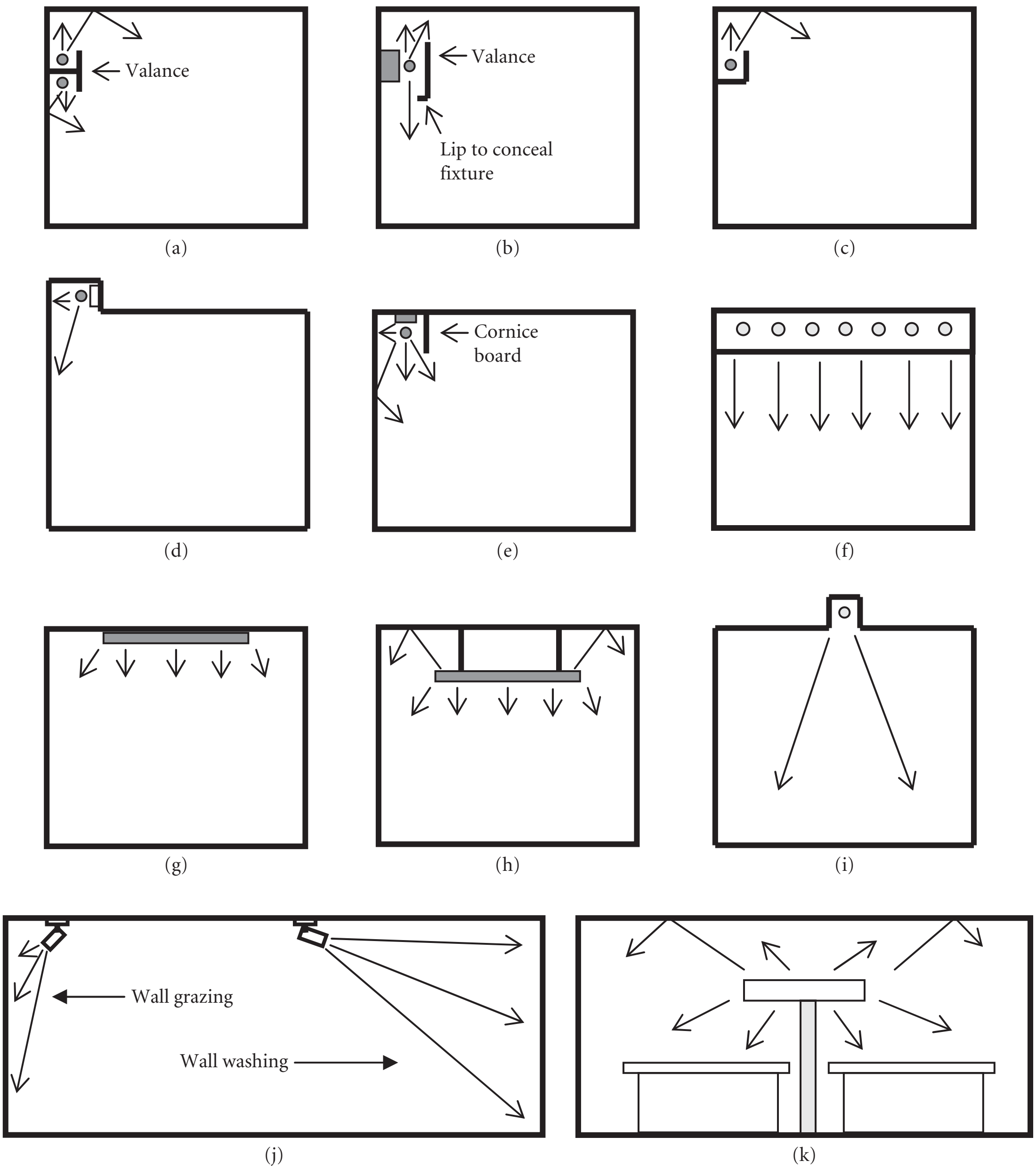


FIGURE 2 Various lighting geometry components. (*a*) and (*b*) Valence lighting. (*c*) Cove lighting. (*d*) and (*e*) Wall slot and Cornice lighting for wall illumination. It can be used to create an effect of a floating ceiling. (*f*) Illuminated ceiling. There is a diffuser below the row of line sources. This scheme can also be used to create illuminated wall panels. Backlighting is another technique. (*g*) Overhead luminaire. (*h*) Suspended luminaire. (*i*) Recessed downlight. (*j*) Wall-grazing and wall-washing illumination emphasizes and flattens the wall textures respectively. (*k*) Furniture-integrated lighting system. In cases (*a*) to (*i*), the sources are lines sources such as fluorescent tubes along the length of the wall. In each case, the neighboring surfaces whether wall or shielding surfaces are coated with high reflectance diffuse paints. The distance of light source from the ceiling/wall determines the uniformity of illumination across the respective regions.

FIGURE 3 Accent lighting. (See also color insert.) (*Courtesy of Pegasus Associates Lighting, www.pegasusassociates.com.*)

the light sources well shielded by the luminaire and baffles to avoid direct glare. For large overhead sources, louvers (Fig. 24*e*) are used to limit the direct source view. Veiling reflections are avoided by ensuring that the source-task-eye geometry does not direct the reflections off the task into the eye.

Decorative lighting, as the term implies, is used to add sparkle to the lit environment. Decorative lighting is most effective when it appears to provide most of the lighting in a scene. Using decorative lighting to provide other functions of lighting by increasing the lamp brightness is not a suitable solution, although it increases the illumination in the region. It draws too much attention toward the lamp itself and creates undesirable levels of source brightness against the background leading to glare and unsightly shadows; therefore, decorative lighting must be immersed in an environment with good ambient light. Decorative lighting is provided by low-wattage table or floor lamps, gas lights, chandeliers, sconces, bare light sources, backlighting, light art, and torchieres. See the use of chandelier in Fig. 5.

Accent lighting primarily provides highlighting of objects such as artwork (Fig. 3), plants and decorative objects within a lit environment. Track lights, adjustable recessed lights, uplights, and backlights are commonly used to provide accent lighting.

Lighting Geometries

Lighting geometries can essentially be broken down into four broad classifications. These classifications are not mutually exclusive.

1. Direct Lighting: Most of the light (>90 percent) from a luminaire is targeted toward a certain region such as in downlighting in an office by overhead light fixtures. Applications of direct lighting include all the lighting functions such as ambient, task, decorative, and accent.
2. Indirect Lighting: An object or a region is illuminated by light that is not directly coming from the source. For example, the light from a lamp is directed toward the ceiling, wall, or even a

FIGURE 4 Wall sconces for providing ambient lighting and the much needed vertical illumination in various situations. (See also color insert.) (*Courtesy of Lightcrafters Inc., www.lightcrafters.com.*)

diffuse reflecting region of the luminaire. The reflections illuminate the space around the luminaire. Indirect lighting tends to give a more spacious appearance and eliminates shadows. Its primary application is to provide ambient lighting. See Figs. 4, 5, and 24*c*.

3. Diffuse Lighting: When lighting does not appear to come from any specific direction. Examples of diffuse lighting include indirect lighting and certain direct lighting geometries such as overcast skies, large area lighting fixtures with diffusing or prismatic optics or large spatial extent fluorescent lamps. It is mostly used for ambient illumination but can also be used to create local areas of high and uniform brightness for task lighting or accent lighting.
4. Direct-Indirect/Semi-Direct/Semi-Indirect Lighting: These terms typically apply to lamps that distribute some portion of their light toward the target and the remaining portion toward a surface that reflects (specular and/or diffuse) light toward the target. Semi-direct typically refers to the case where 60 to 90 percent of the light is directed toward the target while semi-indirect refers to the case where 60 to 90 percent of the light is directed away from the target. Applications include all the lighting functions: ambient, task, accent, and decorative. See Fig. 24*d* for an example of direct-indirect lighting fixture.

Figure 2 illustrates several implementations of these lighting geometries[5] within the confines of indoor lighting. A practical lighting layout is likely to include one or more of these concepts.

FIGURE 5 Indirect lighting with cove lighting in a restaurant using light strips. The chandelier provides the decorative lighting without significantly contributing to any other lighting function. (See also color insert.) (*Courtesy of Pegasus Associates Lighting, www.pegasusassociates.com.*)

Properties of Objects and Their Impact on Lit-Scene

Objects in a lit-scene have geometrical (shape, location, and orientation) and optical properties (wavelength dependent absorption, reflection, transmission, and diffraction). Reflection and transmission include both diffuse and specular components. Lit-scene characteristics are then in-part determined by geometrical and optical properties of the objects and also in part determined by the interaction of these characteristics with the light sources in the environment. The object-light source interaction gives rise to such phenomena as glare, nonuniform illumination and color change. Major indoor features that impact a lighting environment are walls, floors (including large area carpeting) room partitions and ceilings. Minor features consist of temporary objects such as wall coverings, furniture, partitions, art, displays and plants. Major outdoor features that impact lighting environment are ground, buildings, vegetation, distant and close landscape features. Minor outdoor features are temporary objects.

System Layout and Simulation

Based upon the lighting design criteria, appropriate lamps with desired lighting schemes are selected. However, to obtain the desired illuminance distribution over time, appropriate calculations and simulations are needed. In this section, we discuss the tools for system simulation.

For any given system layout, a certain light level is needed. Equation (11) provides an approximation of the number and type of luminaires needed to obtain a certain horizontal illuminance over a work plane. This equation is useful when expressed as a summation of individual luminaires with their specific constants.

$$E_{\text{maintained}} = Fn\,\text{LLF}\,\text{CU}/A \tag{11}$$

where $E_{\text{maintained}}$ = average illuminance maintained
F = total rated luminaire lumen
n = number of luminaires

CU = coefficient of utilization (It defines the percentage of light from the lamp reaching the work plane. CU depends upon the relative placement of lamp and work plane and illuminance distribution at the work plane corresponding to the geometry.)
A = work plane area
LLF = total light loss factor

LLF[27] accounts for the lamp output reduction over time. LLF has both recoverable and nonrecoverable components. Nonrecoverable factors are due to permanent degradation of the luminaire surface, reduction of output due to deviation from ideal operating temperature and environment (convection and ambient temperature), inefficiency of the electronic drive components and deviation in the operating position (tilt) from the ideal position. Recoverable factors are those whose effects can be mitigated by regular cleaning of the luminaire, operation in a clean environment, and regular replacement of bulbs or sources upon their natural degradation with time. LLF is a product of all these factors. Many of these factors also affect the intensity profile of the lamp output and can therefore affect the CU. The *Lighting Handbook* by IESNA[28] lists a detailed procedure for calculating the room surface dirt depreciation factor and luminaire dirt depreciation factor. Other factors can be obtained either by lamp manufacturer specification data or by measurement in an as-used configuration of each lamp before use.

System simulation can be done in two ways: manually or using specialized software. To do it manually, the lumen method [see Eq. (11)] and the zonal cavity method are used. The zonal cavity method[29] involves modifying the CU by calculating the effects of room geometry, wall reflectance, luminaire intensity, luminaire suspension distance and workplane height. The impact of various parameters is available in the form of look-up tables that can be consulted to provide estimates. These methods are quite powerful but outside the allowable space in this chapter, please consult the mentioned references.

System simulation with specialized software allows unparalleled accuracy and flexibility. Modern software tools allow easy modeling of 3D geometries, material and source properties. Sophisticated analysis tools allow for calculation of luminance, intensity, illuminance and chromaticity at any location, and they also provide photorealistic rendering of lit models that account for specular as well as diffuse reflections. Accurate system modeling involves the following steps:

1. Model the 3D geometry of the lit region. Windows, skylights, and light shelves must be modeled with their coverings: blinds or glazings with their optical properties.
2. Model the surfaces and paints. The reflectance is a combination of specular and diffuse components. For those surfaces and paints that cannot be simply described by specular or Lambertian properties, the bidirectional reflectance distribution function (BRDF) is used.[30] The dependency of BRDF is composed of the incident direction and the direction of observation. This concept has been explained in much more detail in Chap. 7, "Control of Stray Light," in this volume. BRDF measurements are mostly obtained experimentally. These measurements are available sometimes by paint vendors or makers of specific surfaces. It is also possible to simulate BRDF approximately by assigning texture and reflective properties to the surface and performing a ray trace. Once the reflectance properties of each surface are available, they are assigned to the surfaces in the optical model and allow accurate photorealistic rendering of the model for all cases of source and viewer locations.
3. Model the lamps: luminaire geometry and source model. Source models are increasingly being made available by the lamp vendors. If the model is not available, source measurements may be needed. Source models consist of a collection of rays that represent the output from the source. Each ray is described by its position and direction cosines in 3D space. Daylight can be simulated by creating two sources outside the model: sun and sky and assigning diffuse reflective properties (10 to 20 percent) to the ground outside the model. There are a variety of ways to model the sun. One way is to represent it as a Lambertian disk of its angular extent (0.52°) and a luminance value that provides the insolation on the earth's surface at the geographic location (~1000 W/m^2). The final step is to locate the Sun's position relative to the model. The sky is modeled as a large Lambertian disk of a prescribed luminance. For example, a clear sky is represented by 8000 nits and an overcast sky is represented by 2000 nits.
4. Decide upon the location of the measurement surfaces. These could be real or virtual. A photorealistic scene rendering helps in realizing the most promising layouts.

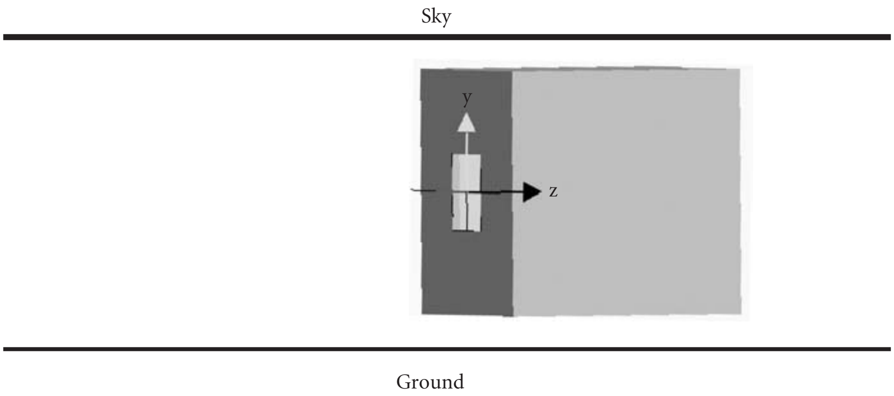


FIGURE 6 System layout. (Source: Clear sky 8000 cd/m^2. Room Size: 3 m × 3 m. Window size: 1 m × 1 m. Window location: center of the wall. Wall reflectance: 35 percent. Roof Reflectance: 60 percent. Floor reflectance: 40 percent. Ground reflectance exterior to room: 20 percent.)

Figures 6 and 7 show an example that illustrates the above steps.[31] We simulate a room with one window. All the light received in the room is daylight from a clear sky. In this example, we calculate the light distribution across the floor for two cases: with and without assuming that the room surfaces are diffuse reflective. Figure 7 shows the impact of including reflectances from various objects which results in a wider spread of illumination across the floor.

It is easy to make the model more complex by adding internal light sources, objects with a variety of surface properties, skylights, influence of sun and so forth. Next, we discuss the software tools available to perform such simulations.

Software Tools There are extensive software tools to assist the lighting designer in simulating illumination systems. The software includes computer-aided design (CAD), source modeling, optical analysis and design, and computer graphics. Each of these plays a crucial role in the design process, so they are described in the following subsections. Some of the software areas have applicability in a number of aspects of the design process. Finally, we do not mention the explicit names of the software packages since they are continuously evolving, and we make use of certain ones in our daily lives, so we do not want to bias the discussion presented here.

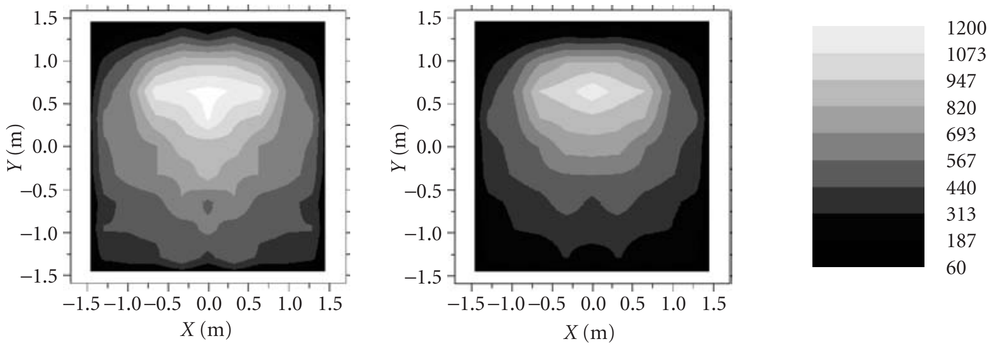


FIGURE 7 Horizontal illuminance (lux) on the floor (*a*) with and (*b*) without taking into account the room reflectance.

CAD software Computer-aided design software is used to build the geometry of any system and is then interfaced with machine tools to fabricate the components. Lighting design makes great use of CAD software to ease the process of integration of complex optical components and the mechanics that hold them and the electronics. Not only are there self-standing, mechanical CAD software packages, but native CAD geometry generation capabilities in the optical analysis software packages discussed later. The latter provide a wealth of tools for the generation of complex illumination systems, but they do not have the range of tools that mechanical CAD software provides. The software can be broken down into two subsets: surface based and solid based. The former implies that each surface is defined separately (e.g., a cube is made up of six separate surfaces), while the latter implies that each object is defined (e.g., a cube is made from one function call). Of course tools are provided in each code such that the design process is simplified (e.g., in a surface-based code a macro could generate all of the six surfaces of the cube with one function call). Solid-based codes tend to provide a more efficient process to enter the geometry of the system, but surface-based codes have a longer market history. None of the mechanical CAD packages provide optical analysis and design tools, but they do provide hooks to integrate into them. In fact, some of the optical analysis and design software companies have developed plug-ins that allow the user to specify optical characteristics such as materials and surfaces. These tools assist with the design process by requiring only one iteration of assigning such properties and simplify the transfer of the geometry to the optical analysis software. The transfer of the geometry is typically accomplished by two formats: International Graphics Exchange Specification (IGES) and Standard for the Exchange of Product model data (STEP). Other protocols including proprietary ones, DXF, DWG, STL, and SAT are understood by certain optical design and analysis tools.

IGES IGES is a standard first published in 1980 by the National Bureau of Standards (now the National Institute of Standards and Technology, NIST) as NBSIR 80–1978, and then approved by an ANSI committee as Version 1.0.[32] It was first known as Digital Representation for Communication of Product Definition Data. It is essentially a surface/curve-based method to represent the geometry that comprises a component or system. The IGES standard was updated through the years, with Version 5.3 in 1996 being the last published version.[33] STEP (see the next section) was to replace IGES, but IGES remains the prevalent neutral-based method to transfer geometry data. Most optical analysis codes can read and interpret various versions of IGES, but the surface-based optics codes tend to have better performance (i.e., fewer import errors).

STEP STEP is a standard first published in 1994 by the International Standards Organization (ISO) as ISO 10303 with the goal of replacing IGES. It is essentially a solid-based method to represent a system, but it also has 2D and database aspects.[34] It has been updated through the years and is now comprised of many part and application protocols. STEP is developed and maintained by the ISO technical committee TC 184, Technical Industrial automation systems and integration, subcommittee SC4 Industrial data.[35] Most optical analysis codes can read and interpret various versions of STEP, but the solid-based optics codes tend to have better performance (i.e., fewer import errors).

Source modeling software In order to perform accurate simulation of a lighting system it is imperative that an accurate source model is used. There are essentially three methods to accomplish this:

- Generation of ray data based on manufacturer data sheets
- Experimental measurements of the emitted radiation to create ray sets
- Modeling of the geometry of the source and the physics of emission to create ray sets

The first method creates either ray sets or Illuminating Engineering Society (IES) intensity distributions that can be used to model the performance of a lighting system that incorporates the prescribed source. The second, experimental measurement uses a goniometer or similar device to measure the output of the source both as a function of position and angle; therefore, it measures the luminance distribution of the source. The last is based on modeling of the source components, such as filament, base, and glass envelope in an incandescent bulb; electrodes, glass envelope, and base for an HID lamp; and die, epoxy dome, and reflector cup for a LED. Based on the physics of the source, rays are assigned to the emission areas. A number of optical analysis software companies are providing geometrical and ray source model libraries to their customers. All three methods are based on the data, measurements, or model of a single source, called the nominal source. Thus, there is the opportunity for error between the nominal source and what is used in your fabricated system.

Source manufacturers and architectural lighting software tend to use the IES source files to specify their sources. These files are not as precise as the other two methods, but they provide a good enough and fast method to implement the source emission characteristics into the design process. Companies that make these accurate experimental measurements keep libraries of the data, so that their customers can include them in their lighting system models. The CAD software allows a designer to make a complex model of the source, and then the optical analysis software allows the rays to be generated. This method also provides accurate source models, but with the only time expenditure to develop such models. It has been found that methods that employ both the geometry and experimental emission measurements provide the highest level of accuracy while also giving an avenue to model the tolerances of the emission.[36,37]

Optical modeling software As previously stated, optical analysis and design software not only allows for the modeling of optical systems, but it also provides tools for inclusion of geometry, source modeling, and rendering (discussed later). There are both solid-based and surface-based codes. Most optical phenomena occur at the surface interfaces, such as reflection, refraction, scattering, and diffraction, but there are volume effects, such as scattering, absorption, and emission. Therefore, though a single software packages is based around solids or surfaces, it must be able to effectively model the other type of phenomena. A number of the codes are generic in nature, such that they can handle virtually any type of system or application, from backlights to luminaires to biomedical applications. There are application specific codes in a number of areas, especially external automotive lighting and architectural illumination. The software is increasingly adding tools such as source modeling macros, optimization, tolerancing, and rendering.

There are essentially three types of software packages that can be used to model a lighting system: optically based ray tracing, lighting-based radiosity, and computer graphics rendering. Ray tracing is simply the tracing of a multitude of rays from sources through the optical system. It is quite accurate, only limited both by the characterization of the geometry and the assigned optical properties within the model and the number of rays that are traced. Radiosity algorithms are essentially scatter-based methods that propagate approximate wavefronts from one object to another. Initially, Lambertian scatter properties of all objects were assumed, but more recently radiosity implementations propagation based on the bidirectional surface distribution function (BSDF), generally, or the respective reflective (BRDF) or transmissive (BTDF) forms, specifically, have been developed.[38] Ray tracing can handle both specular and diffuse reflections, but radiosity is limited to diffuse reflections. Ray tracing has a number of benefits including accuracy and utility from the near field to far field. Radiosity is for the most part limited to far field calculations, where the approximations of the propagation model are minimized. As the distance between the source and target is reduced, the limitations of the scatter-based propagation inhibit accuracy. The primary limitation of ray tracing is the calculation time, which is several orders of magnitude more than radiosity. Thus, hybrid methods that employ both ray tracing and radiosity are in use. The goal of hybrid methods is to obtain the benefits of both ray tracing and radiosity in a single algorithm.

In the next three subsections the three types of software packages are discussed in more detail. Notably, the lines between these three types of software packages is disappearing, especially between the lighting design and computer graphics sectors. In each of these sections the applicability to lighting design and modeling is provided. These software packages are seeing rapid growth, so consultation of the literature on active research on future development is suggested.

Optical design and analysis software There are two types of optical design and analysis software: imaging system software and general analysis software. The first is typically called lens design software, and has limited utility to the design of lighting systems. The second uses nonsequential ray tracing from the source to the target. This process allows the illumination distribution at the target to be accurately determined. This type of software often includes, at the discretion of the user, such features as spectrum, coherence, polarization, and so forth. Thus, the accuracy is only limited by the user input. The design of the actual luminaire is best done with this type of software. It allows the designer to design efficient systems that effectively couple and broadcast the emission from the light source. These codes also provide tools for optimization and tolerancing of the luminaire. However, due to lengthy computation time, optical design and analysis codes have limited (but increasing, due to the advances in computer speeds) utility in determination of a lit scene (i.e., rendering).

Lighting design software Unlike optical design and analysis software, lighting design software typically makes use of radiosity algorithms.[39] Radiosity codes are quite fast and have acceptable accuracy in the far field. The use of Lambertian or BSDF scatter properties allows the diffuse reflection from objects to be quickly ascertained and propagated further into the system. The diffuse emission is both collected at the observation location and is cascaded to other objects in the scene. In order to obtain a higher convergence speed objects are typically parameterized with polygons, while optical phenomena such as refraction or specular reflection are approximated or even ignored. This type of software thus provides at worst a first-order approximation of the lit appearance such that architects and lighting designers can view the results of their design work. Lit-scene rendering or illumination in the far field of a luminaire is the best use of lighting design software. More advanced software packages can then be employed, such as those that employ some semblance of ray tracing—see the previous and next sections.

Computer graphics software In the past two decades the computer graphics community has grown rapidly. The tools they develop and employ are useful in the illumination community of optics. Foremost they have tools to model the simulated look of an unlit or lit lighting system, called unlit-and lit-appearance modeling respectively. These tools are important in illumination since acceptance of a system is often based on subjective criteria such as appearance. Thus, these tools provide such before potential costly and time-consuming manufacture. Additionally, the computer graphics community uses both ray-based and scatter-based radiosity methods, while also employing hybrid methods. These methods are especially geared to the rendering of scenes in video games, movies, and other types of visual media. Thus, they tend to have the least amount of accuracy since the completion of numerous images in a timely manner is demanded.

Computer graphics software makes direct use of forward ray tracing (from the source to observer) and reverse ray tracing (from the observer to the source). The latter is especially useful for the rendering of scenes where there is a discrete viewpoint, like that of a virtual observer. These codes and algorithms are increasingly being used to model the lit appearance of illumination systems such as luminaires and lightpipes. This process involves some form of ray tracing and/or radiosity calculations and then employs vision biology (Sec. 40.3). As an example, consider a star-shaped taillight as shown in Fig. 8.[40,41] The taillight is oriented at several angles such that the effects of changing ones aspect to the lit taillight is taken into account. The combination of these different angular views of the taillight provides the luminance distribution, or essentially what an observer would see by walking around the lamp. A ray tracing method employing a pupil collection of 15° is used for each of the plots within Fig. 8. Note that saturation of the retinal cones is included, which is evidenced by the whitish appearance of the filament at the center of the lit patterns.

Furthermore, the resulting intensity pattern for the lit-appearance model can be projected into a scene to provide a rendering of what the illumination from the lamp will look like. For example consider Fig. 9, which shows three view aspects of an automobile headlight designed to meet standards (see section on vehicular lighting): (a) the driver's perspective, (b) 20 m above and behind the drive, and (c) the bird's eye view.[42] These renderings are quite accurate since the goal is to completely mimic the lit-scene appearance prior to fabrication. These types of renderings can be extended to any scene that involves sources and objects with accurate optical characteristics applied to them. Figure 10*a* shows the rendering of a south-facing office room[43] in Tucson, Arizona. The illumination was modeled from average direct and diffuse insolation data for November 15 at noon for this location. The CAD model was generated from architectural blueprints of the facility. Surface reflectances were determined from first principles. The scene outside the window was created from a

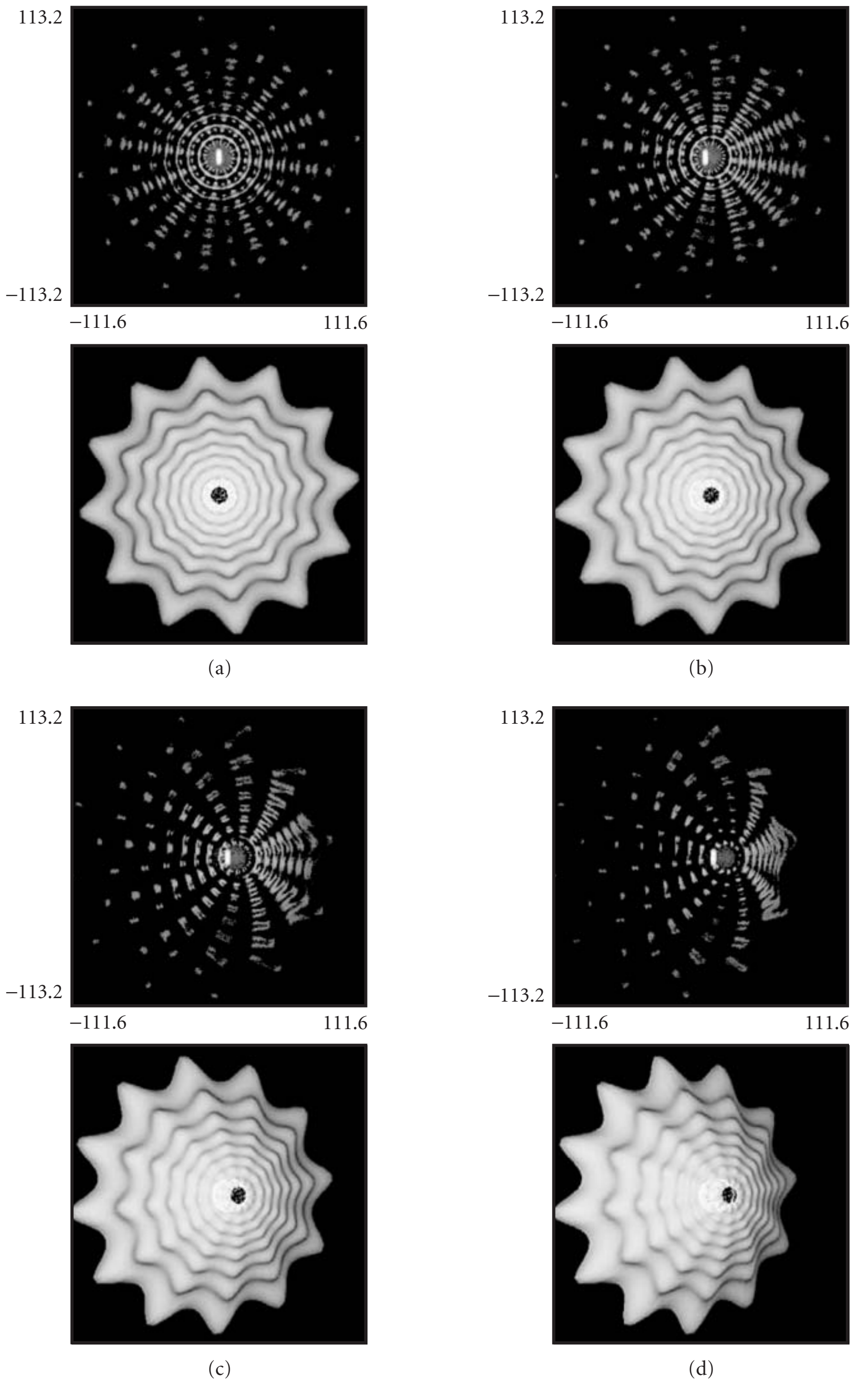
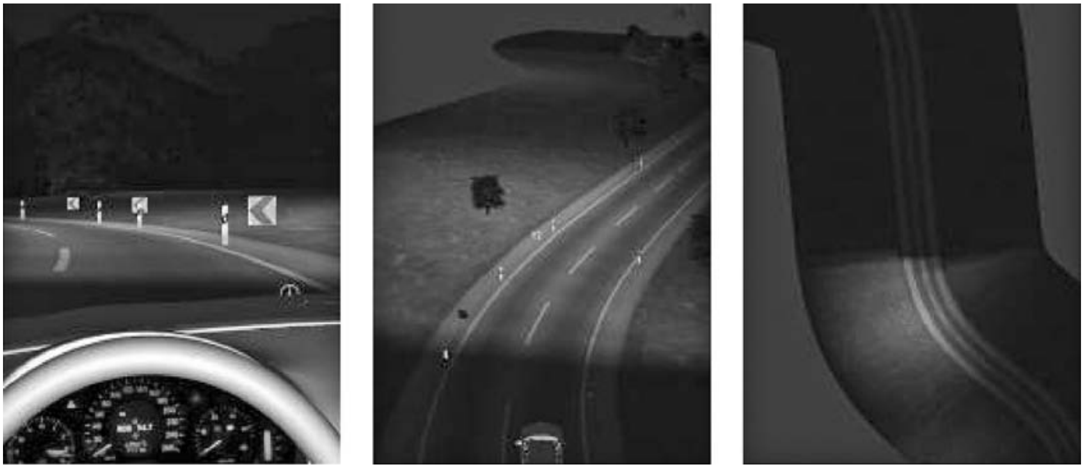


FIGURE 8 Views of the lit appearance (upper) of a star-shaped taillight (lower) at four horizontal angles of (*a*) 0°; (*b*) 10°; (*c*) 20°; and (*d*) 30°. (See also color insert.) (*Used with permission from SPIE;*[40] *Developed with Advanced Systems Analysis Program from Breault Research Organization.*)



(a) (b) (c)

FIGURE 9 Three perspectives of lit-scene renderings from a low-beam headlamp: (*a*) driver's view; (*b*) 20 m above and behind automobile; and (*c*) bird's eye view. (See also color insert.) (*Developed with LucidShape and LucidDrive from Brandenburg, GMBH.*)

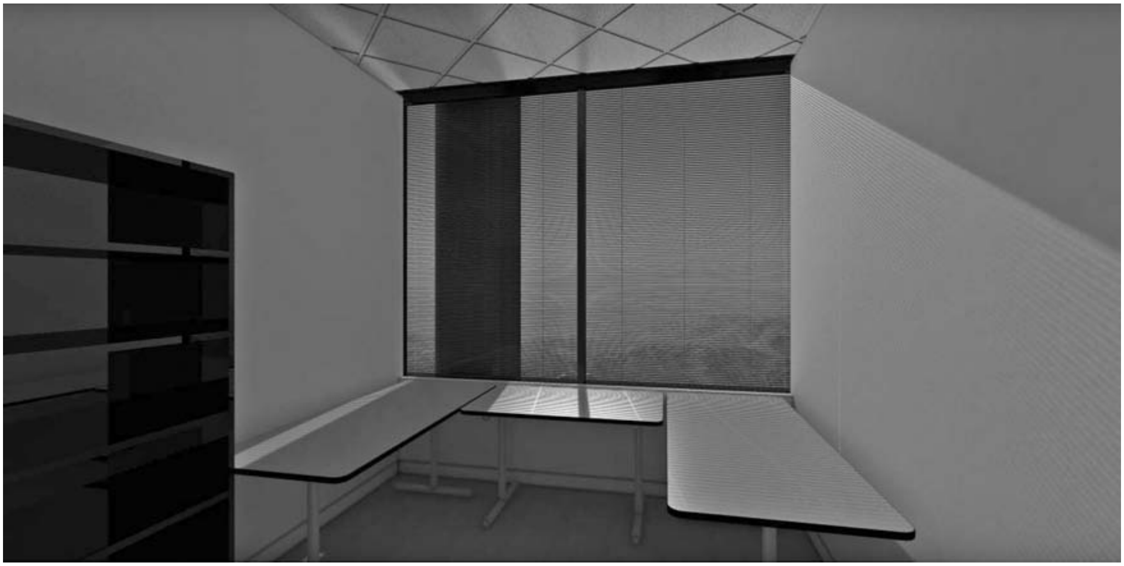


FIGURE 10*a* Rendering of a lit office room. (See also color insert.) (*Developed with LightTools from Optical Research Associates.*)

digital photograph taken in the mountains outside of Tucson. 100,000,000 rays were traced from the source throughout the model. Similarly, Fig. 10*b* shows the rendering of a desk surface lit by interior, incandescent lighting.[44] All surfaces, except the three objects on the desk (shown in wireframe to ease view through the objects), are diffuse Lambertian reflectors. The three objects: wine glass, ice cube, and crystal ball, display the effects of specular refraction and total internal reflection.

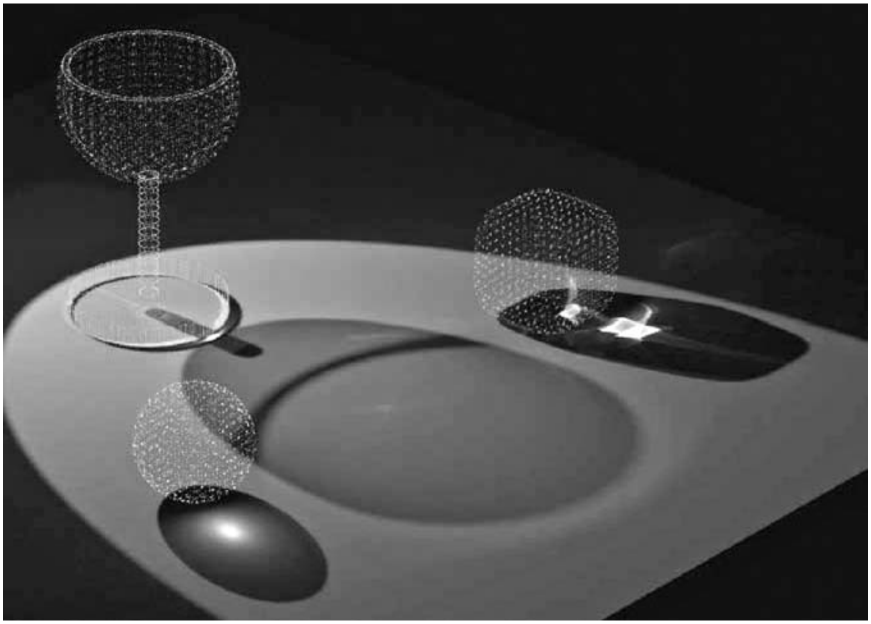


FIGURE 10*b* Rendering of a lit desk with three objects located on it (wine glass, ice cube, and crystal ball) to show both diffuse and specular effects. (See also color insert.) (*Developed with FRED from Photon Engineering.*)

40.5 LUMINAIRES

A luminaire is a packaged light source consisting of emitter, optics to baffle or redirect light, fixture and electrical components. Luminaires form an integral part of the lighting design by the virtue of the illumination they provide and also by their appearances. In this section, we discuss the optical components of luminaires: types of light sources, both artificial and natural (daylight), and the design of luminaires with optical components such as reflectors, lenses, lightguides, fibers, windows, skylights and baffles to achieve the desired light distribution.

Types of Light Sources

Light sources are optically characterized by their luminous spectrum (lumens as a function of wavelength), intensity (in candela), and efficiency (lumens per watt, lpw). For white light, CCT and CRI are derived from the spectrum of the source and are typically reported on the data sheets to give an estimate of its appearance and its ability to color render lit objects. Other source characteristics are cost, safety, government regulations, package size/type, lamp sockets, electrical driver requirements and constraints related to environment or operating conditions. Cost is defined in terms of luminous flux per dollar per hour of use, replacement, and initial installation costs.

We discuss daylighting and the following artificial light sources: incandescent, fluorescent, high-intensity discharge (HID), light-emitting diode (LED), electrodeless HID, electroluminescent, nuclear, laser, bare discharge, low-pressure sodium (LPS), and short arc sources. In the next few subsections we discuss various light sources in terms of operating principles, construction, and packaging. Refer to Table 3, which provides the performance comparison of various lamps; and Table 4, which

TABLE 3 General Lamp Characteristics for Most Lighting Applications

	Watts	Efficacy lpw	CCT K	CRI	Lifetime K hours	Notes
Standard Incandescent	40–100[a]	10–17[T]	2700	>95	0.75	Undesired IR radiation, fire hazard. Naturally low flicker, instant-on and dimming to 0.
Tungsten-Halogen	300[a]	20	2850–3200	>95	<6	Same as standard incandescent.
Fluorescent/ CFL	5–55	15–100 60–70[T]	3000–6500 4100[T]	50–98 70–85[T]	5–20[b]	Complex ballasts for good dimming range, short start-up, low hum, low flicker. Hg disposal issue, EMI.
HID-Hg	50–1000	30–65	3900–5700[c]	15–20 higher with phosphor coatings	16–24	Complex ballasts for start-up and flicker control, poor dimming, high flicker, explosion, fire and UV hazard, lamp disposal issue, high start-up and re-strike intervals, poor color stability with time, operating position affects performance.
HID-MH	30–18 K 50–1000[T]	75–125	2500–6000	60–70	7.5–20	Same as HID-Hg. Lifetime <1 K hours for >10 kW lamps.
HID-HPS	175–1000	45–150	1900–2700	22–85	7.5–24	Same as HID-Hg, CRI is inversely proportional to efficacy. 110 lpw corresponds to CRI 20, CCT 1900–2100 K.
HID-CMH	20–400	70–90	3000–4200	80–96	7.5–20	Same as HID-Hg except for good color stability with time and performance independent of operating position.
Electrodeless	4	60+	2700–6500	50–98	15–30[d], <100[e]	Complex ballast, EMI.
LPS	20–100	80–150	1800	0	14–18	
LED[f]	LEDs (large chip or arrays) are likely to replace most of the existing lamp sources. Efficacy can reach up to and beyond 200[g] lpw with the theoretical limit being the CIE standard observer luminous efficacy curve, lifetimes up to 100 K hours. Key advantages are: fast turn-on times, color tunability, high dimming range, low voltage operation, no Hg or Lead, no UV or IR, no catastrophic failures and scalable packages. Phosphor coated LEDs can provide white light at desired CRI and CCT.					

HID—high-intensity discharge, Hg—mercury, MH—metal halide, HPS—high-pressure sodium, CMH—ceramic mercury halide, Xe—xenon, LED—light-emitting diode, CFL—compact fluorescent lamps, [T]—typical.

[a]Also available in kW. Lifetimes shrinks to a few hundred hours, [b]Regular Fluorescent have typical lifetimes >10 K hours, Compact Fluorescent lamps have lifetimes >5 K hours, [c]CCT 5700 K at CRI 15, CCT 3900 K at CRI 50, [d]developing technology, [e]with integrated ballasts, [f]separate ballast, [g]only light generation efficiency inside the LED die.

lists various lamp types, currently available packages and their applications. Figure 11 shows various lamp packages. The alphabetic designation is explained in Fig. 11. The numeric designation with the letters is the diameter specified in 1/8th of an inch. For example, MR16 refers to a multifaceted reflector, 2 in. in diameter.

Incandescent Sources These are thermal sources that emit electromagnetic radiation from a heated filament, which is a phenomenon known as *incandescence*. Incandescent light sources are being steadily replaced with fluorescent lamps, LEDs, and potentially with electrodeless lamps. Other sources are able to provide similar or improved performance at higher efficiency and lifetime leading to reduced operational costs.

Modern day incandescent sources use a tungsten filament.[45] Tungsten has a high melting point (3382°C), high ductility, high conductivity, and low thermal expansion that make it a preferred material for use as a lamp filament. Tungsten is alloyed with tiny amounts of potassium (60 ppm), aluminum oxide (10 ppm), and silicon (1 ppm) to give it high strength near its melting point. This allows lamp operation close to the melting point, thus improving its efficacy. Sometimes tungsten

TABLE 4 Common Lamp Packages and Applications

	Available Packaging	Current Applications
Tungsten	A-line, elliptical, decorative (B, C, CA, F, G, M), PAR, reflector (R, BR, ER), appliance and indicators (S), tubular (T)	General purpose, 3-way, reader, decorative (chandelier, Globe, ceiling fan), Track and Recessed (Indoor floodlight and spot light), outdoor (post & lantern, pathway, garden & deck, motion-sensing & security, bug light, yard stake), appliances, colored lamp, display, exit sign, freshwater and saltwater aquarium, heat lamp, marine, nightlight, party, recreation vehicle, plant, rough service, sewing machine, shatter resistant, terrarium, vacuum cleaner, airport, emergency, city lighting, projection, photoflood, filmstrip, retail display, restaurants.
Tungsten-Halogen	A-line, decorative (B, G, F, T10), PAR, AR, MR, single ended, double ended	General purpose, 3-way, reader, decorative (chandelier, Globe, ceiling fan), Track and Recessed (Indoor floodlight), outdoor (post & lantern, pathway, garden & deck, motion-sensing & security, yard stake), camera light, microfilm, curio cabinet, display, enlarger & printer, equipment, fiber optics, landscape lighting, projection, stage & studio, torchiere, airport, emergency, city lighting, special service, monuments, museums, heat lamp.
Fluorescent (Linear)	Straight linear (T5, T6, T8, T10, T12), circular (T9), U-shaped (T8, T12), grooved (PG17)	Kitchen, bath, shop, work light, Appliances, blacklight, blacklight blue, cold temperature, colored lamp, freshwater and saltwater aquarium, plant, shatter resistant, terrarium, stage & studio, projection, diazo reprographic, germicidal, gold UV blocking, superstores, warehouses.
Compact Fluorescent	Plug-in (2-pin, 4-pin, proprietary), self-ballasted (decorative, reflectors, proprietary)	General purpose, reader, decorative (chandelier, Globe, ceiling fan), Track and Recessed (Indoor floodlight and spot light), outdoor (post & lantern, pathway, garden & deck, bug light), appliances, blacklight blue, facilities, hospitality, office, plant, restaurant, retail display, saltwater aquarium, terrarium, torchiere, warehouse.
HID - Hg	A-line, elliptical, reflector	Street lighting.
HID - MH	Elliptical, PAR, single ended, double ended, tubular	Street lighting, sports lighting, decorative lighting of architectural wonders.
HID - HPS	Elliptical, double ended, tubular	Street lighting, horticulture.
HID -CMH	Elliptical, par, single ended, double ended, tubular	Track and Recessed (Indoor floodlight and spot light), retail display.
Miniature	B, G, R, RP, S, T, TL, discharge	Outdoor (post & lantern, pathway, garden & deck, motion-sensing & security, yard stake), automotive (headlamp, fog, daytime running, parking, directional front & rear, tail, stop, high mount stop, side-marker front & rear, backup/cornering, instrument, license plate, glove compartment, map, dome, step/convenience, truck/cargo and under hood), flashlight, landscape lighting, low voltage, marine, telephone, traffic signal, emergency.
Sealed Beam	PAR, rectangular	Outdoor (motion-sensing & security, yard stake), automotive headlamp, railway, shatter resistant, stage & studio, directional lighting, aircrafts, tractors, airport, emergency, city lighting.
LPS	Tubular	Street lighting, parking lots.
Electrodeless	T, P	Any application where long lifetimes and high efficacy are needed due to high replacement costs and/or difficult access. Road signs, warehouses.
LED	MR16, miniature (2, 3, 5 mm)	LEDs can potentially replace most of other light sources being used for various applications. Currently being used in building interiors (homes, offices, commercial places such as health clubs, hospitals rooms) stairways and pathways, flashlights, traffic lights, signs, digital projection, instrument indicator panels, backlighting applications, decorative, display.

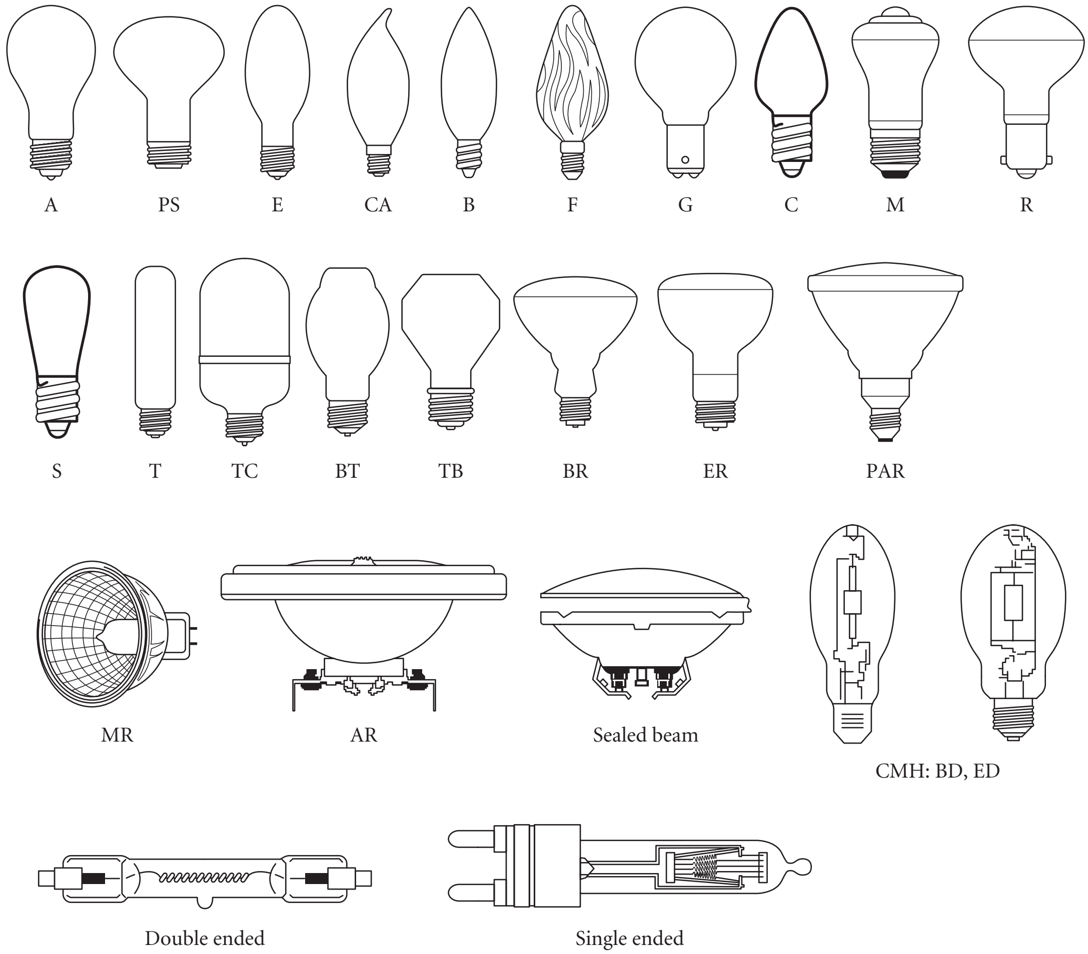
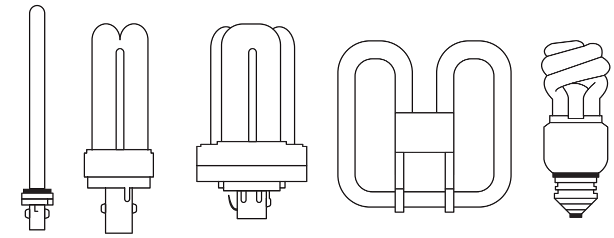


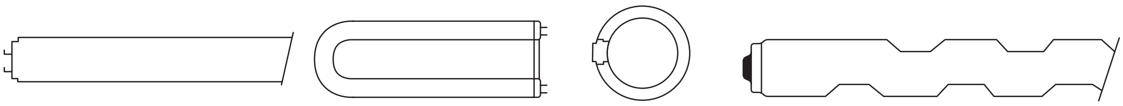
FIGURE 11*a* Various lamp package representations. Shape and sizes are not to scale. Various sizes are available for each package type. For each bulb shape, a variety of bases are available. A—arbitrary spherical shape tapered to narrow neck, B—bulged or bullet shape, BT—bulged tubular, C—conical, CA—conical with blunt tip, E—elliptical, blunt tip, ED—elliptical with dimple in the crown, F—flame shaped, decorative, G—globe, M—mushroom-shaped with rounded transitions, MR—multifaceted reflector, PS—pear shaped with straight neck, PAR—parabolic aluminized reflector, BD—bulged with dimple in crown, S—straight, T—tubular, TB—Teflon bulb, TL—tubular with lens in crown. (*Illustration courtesy of General Electric Company.*)

is alloyed with rhenium (3 to 25 percent) to make it more ductile at low temperatures and achieve higher recrystallization temperatures thereby giving the lamp a longer life. Alloying tungsten with thoria provides increased strength, better machinability and high recrystallization temperatures. Such filaments are used for very high voltage applications.

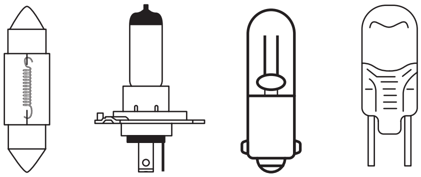
Figure 12 shows the radiating characteristic of tungsten at 3000 K and its comparison with a blackbody emitter. It differs from the blackbody due to wavelength-dependent low emissivity. A perfect blackbody has an emissivity of one for all wavelengths. The hotter the filament, the higher are the luminous flux radiated per watt, the percentage of luminous flux of the total radiation, and the CCT. However, the lifetime is inversely proportional to the filament temperature as filament evaporation is



CFLs: Biax, double biax, triple biax, 2D, spiral



Fluorescent T, U-line, circline and grooved PG



Miniature: neon, festoon, automotive, TL

FIGURE 11*b* Various lamp package representations. Shape and sizes are not to scale. (*Illustration courtesy of General Electric Company.*)

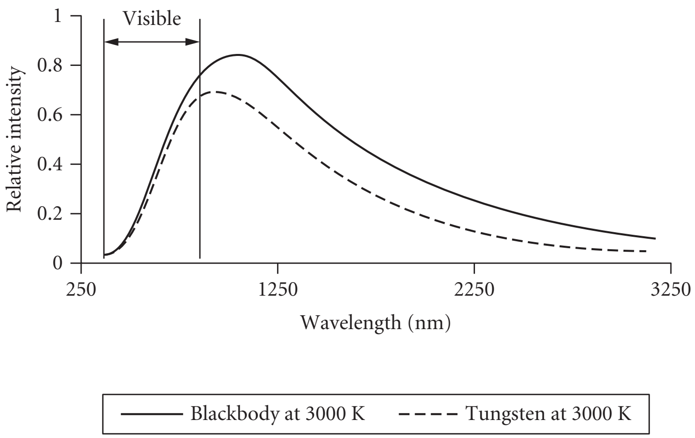


FIGURE 12 Blackbody at 3000 K versus tungsten filament at 3000 K.

the primary mode of lamp failure. The best engineered solution consists of the hottest possible lamp filament at an acceptable lifetime, voltage rating, and packaging. Near its melting point, an uncoiled tungsten wire has a luminous efficacy of 53 lm/W. To achieve an acceptable lifetime, the tungsten filament is operated at much lower temperatures. The luminous efficacy of typical incandescent lamps with tungsten filaments ranges from about 5 to 20 lm/W for lamp wattages 5 to 300, respectively.

A typical incandescent lamp consists of an evacuated glass envelope; filament, with or without fill gases; filament leads; and base. Figure 13 shows the key characteristics.

The bulb material is application dependent. For most applications soda lime glass is used. For applications requiring heat resistant glass, borosilicate, quartz, or aluminosilicate is used. When the bulb envelope is frosted from the inside or coated with powdered silica, it provides diffuse illumination from the bulb surface and masks the bright filaments from direct view. The bulb envelope material can be used to filter the radiation to alter the CCT. Daylight application bulbs filter out the longer wavelengths to provide a higher CCT.

Lead-in wires are made of borax coated dumet (alloys of nickel, copper, and iron). Dumet is able to form a glass-metal seal. It is important to match the thermal expansion of the lead-in wires with the envelope material. When high bulb-envelope temperatures are involved, molybdenum strips bonded to lead-in wires are used for glass-metal seals. The bulb base is cemented to the bulb envelope and is designed to withstand the operating temperatures. The filament itself comes in various configurations depending upon the application. Various filament configurations are a straight wire (designated as S),

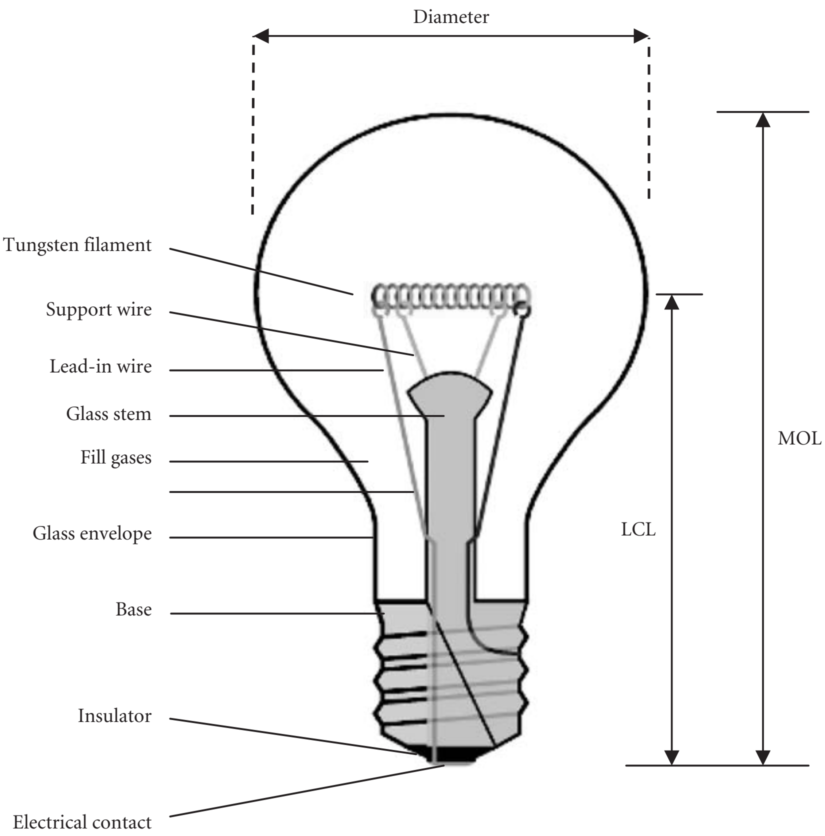


FIGURE 13 An incandescent bulb. (MOL—maximum overall length, LCL—light center length.) (*Adapted from Wikimedia Commons.*)

a coiled wire (designated as C) or a coiled coil (the coiled wire is further coiled onto itself, designated as CC). See Fig. 16 in Chap. 15, "Artificial Sources," in this volume. Coiling increases the surface area per unit length of the filament as well as volume packing density. This allows higher operation temperature at higher efficiency due to relative reduction in heat lost to convection. Multiple supports are used to reduce filament vibration. The number and type of supports depend upon the bulb operating characteristics. A higher number of supports is needed for rough/vibration service lamps. These lamps have low wattages and efficiency and operate in environments that involve shock and vibration for the lamp. Heavier filaments withstand vibrations much better and need fewer filament supports.

Fill gases at low pressure are used to prolong the lamp life at high operating temperatures (high efficacy and power) by reducing the evaporation rate of tungsten. For most applications, mixtures of argon and nitrogen are used as fill gases. More expensive gases such as krypton and xenon are added to the mixture when the higher efficacy justifies the cost increase. Bromine is added to create a new class of lamps called tungsten-halogen lamps which we discuss next.

Tungsten-halogen lamps operate at substantially higher temperatures leading to higher CCT and efficacy. In addition, they have longer lifetimes. At high temperatures, evaporated tungsten combines with the halogen gas and forms a gaseous compound. This gaseous compound circulates throughout the bulb via convection. When this gaseous compound comes in contact with the hottest parts of the lamp such as electrodes the halogen compound breaks down. Tungsten is re-deposited on the electrodes and the halogen is freed up to take part in the halogen regenerative cycle. For the halogen regenerative cycle to work, the bulb envelope must reach a high temperature (>250°C). At lower temperatures, the tungsten will deposit on the bulb envelope instead and lead to lamp blackening and filament thinning, a common failure mode of incandescent lamps. Operating a tungsten-halogen lamp at less than the rated voltage inhibits the halogen regenerative cycle and takes away the longevity advantage. Tungsten halogen lamps have relatively compact bulb envelopes to allow for high bulb-envelope temperatures. The bulb envelope may also have an IR reflective coating to enhance the heat density inside the bulb. Compact bulb sizes make them good candidates for use with reflectors (such as a PAR) to provide directional properties for the lamp emission. The bulb envelopes for such lamps are made of heat resistant material to withstand high temperatures. The high filament temperature in halogen lamps generates UV. The UV rays must be blocked by a UV absorbing lamp cover or UV absorbing but heat resistant bulb envelope such as high-silica or aluminosilicate.

Flicker in incandescent lamps is naturally very low due to slow response of filament temperature to voltage fluctuations caused by power supply frequency or noise.

Incandescent lamps fail when bulb blackening or filament notching (thinning of the filament by evaporation) reduces the output substantially or the filament breaks either by vibration or by complete evaporation of some filament portion. With the exception of halogen lamps, operating the incandescent lamps at less than rated voltage dramatically extends the lifetime (by reducing the filament evaporation rate) at the cost of reduced efficacy, CCT, and luminous flux. In situations, where long lifetimes are needed such as when the lamps are located in a hard to replace areas and/or under tough environmental conditions, heavy filament lamps that are operated at less than the rated voltage are used. But using lower operating voltage to extend the lifetime is not always economical once the increased cost of electricity due to reduced efficacy and compensation of the reduced flux by using more bulbs is taken into account.

Fluorescent Lamps These are luminous sources based on light emission by excited states of phosphors, a phenomenon known as *fluorescence*. These phosphors are typically excited by UV emission due to spectral line transitions across gases such as mercury vapor and/or rare gases such as Xe and Ar. Most commonly available fluorescent lamps are mercury-vapor-based although mercury-free fluorescent sources are available. Phosphors are now available that are excitable by visible light. Such phosphors are also being used for LED-based light sources to produce white light. Fluorescent lamps are actively replacing incandescent light sources and in many cases are themselves being replaced by LEDs.

As shown in Fig. 14, a fluorescent lamp consists of a closed tubular fluorescent material coated glass envelope filled with low-pressure mercury vapor, electrodes at each end of the tube and a ballast to provide high-strike voltage across the electrodes and limit the current during operation. A high-strike voltage across the electrodes initiates a gas discharge in the mercury vapor with light

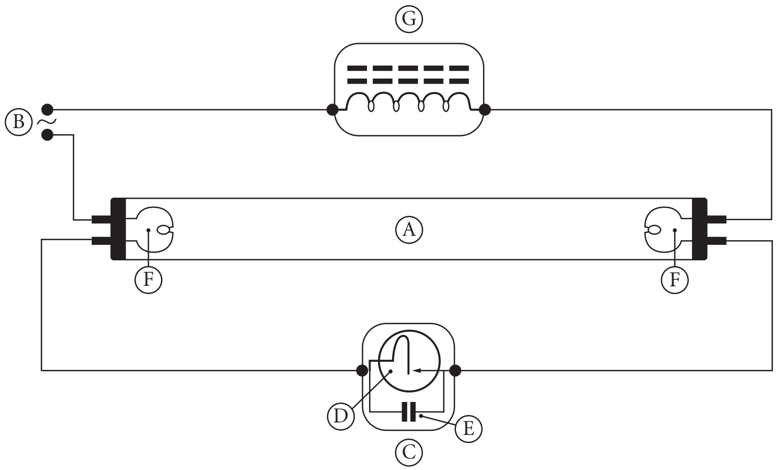


FIGURE 14 A preheat fluorescent lamp circuit using an automatic starting switch. A—fluorescent tube with fill gases, B—power, C—starter, D—switch (bimetallic thermostat), E—capacitor, F—filaments, and G—ballast. (*Courtesy of Wikipedia Commons.*)

emissions across various wavelengths. The UV emission lines of mercury, mostly at 254 nm, excite the phosphors coated on the inside of the tube, cause them to fluoresce and lead to emission in the visible. The fill gases consist of mercury vapor at low pressure (10^{-5} atm) for UV emission and mixtures of inert gasses such as argon, krypton, neon, or xenon at a relatively higher pressure (10^{-3} atm). Inert gases help in lowering the strike voltage across the electrodes as discussed later.

Mercury-free fluorescent lamps mostly use excimers (excited dimers of rare gases and/or their halides with Xe being popular) to produce UV to excite the phosphors. High-wattage operation and high lifetime is achievable but the efficacy is low as compared to the mercury-based lamps. Xenon-filled fluorescent lamps are also available but far less efficient than excimer based. Both excimer and Xe-based fluorescent lamps have additional advantages: instant-on, instant restrike, and color stability.

Fluorescent lamp envelope material is made of soft soda lime glass. This glass material blocks all UV. The length and diameter of the fluorescent tubes affect the efficacy and operating characteristics (voltage, current, and temperature). Longer tubes need higher voltage and power but provide higher efficacy. The efficacy is optimized for a certain tube diameter. To reduce the angular extent of emission, fluorescent tubes are coated across a prescribed region for high reflection in the visible. In such cases, only the uncoated regions of the tube emit light.

The fluorescent coating consists of different mixtures of phosphor salts.[46,47] Phosphor salts consist of oxides, sulfides, selenides, halides, or silicates of zinc, cadmium, manganese, aluminum, silicon, or rare earth materials. Inclusions to the base phosphor material help tailor the emission characteristics. There is a large variety of phosphors available. Each phosphor emits light in one or more narrow wavelength bands. A fluorescent coating consists of one or more phosphor materials to produce a desired CRI and CCT for white light emission or specific spectral characteristics. Halophosphates (wide band) and triphosphors (blends of three narrow band red, green, and blue rare-earth phosphors) are commonly used for general lighting applications. Figure 15 shows an example of the spectrum from a halophosphate phosphor. Figure 17 shows the spectrum of a standard fluorescent lamp.

Due to the variety of fluorescent lamp spectra available, it is possible to achieve the desired CCT, CRI, and color requirements of an application. For example, an application may require a specific blend of white light such as "warm white" (CCT 3000 K, CRI 53), "cool white" (CCT 4100 K, CRI 62), "daylight" (CCT 6500 K, CRI 79), or special requirements such as aquarium lighting for providing optimal plant and coral growth and color enhancing of the display. CFLs use triphosphor coating to produce a high CRI (>90) in order to effectively replace the incandescent lamps. Special application

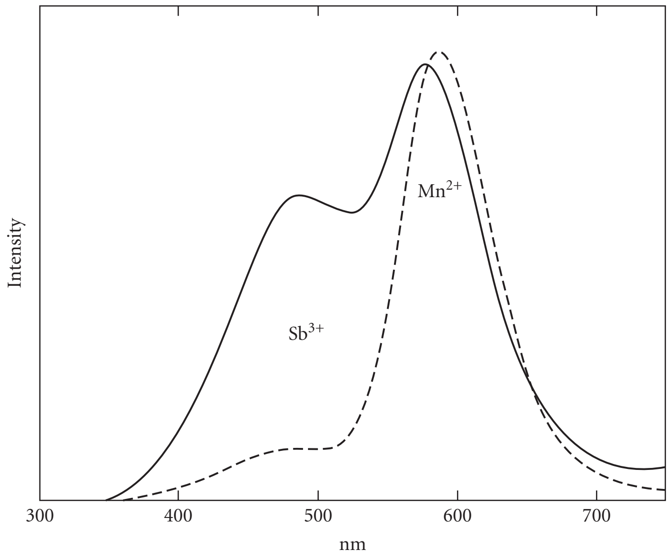


FIGURE 15 Emission spectrum of halophophate phosphor:[47] Sb^{3+}, Mn^{2+} activated $Ca^5(PO_4)^3(Cl, F)$. The ratio of Sb^{3+} and Mn^{2+} species can be adjusted to adjust the spectral distribution.

fluorescent lamps include backlight and tanning lamps. These lamps have phosphors that convert short-wave UV into long-wave UV for applications in tanning (UVA and UVB), detecting materials that fluoresce at long UV (urine, paints, or dyes), or attracting insects.

The lamp electrodes are coated with materials such as oxides of barium, calcium, and strontium to provide low-temperature thermionic emission (electron emission from a heated electrode). Under a potential, these electrons accelerate and ionize the inert gas atoms by impact ionization. Each ionization event generates more electrons that are available to accelerate and further ionize leading to an avalanche that rapidly lowers the gas conductivity. Eventually mercury atoms are ionized. The operating voltage drops and a steady current is established. UV is emitted by transitions across the excited states of mercury atoms. The electrodes can be operated in either of the two modes: cold cathode (arc mode) or hot cathode (glow mode). In the hot cathode mode, the electrodes are preheated to improve the thermionic emission and lower the strike voltage. To enable preheating, electrodes at each end are in an incandescent bulb-like configuration with a tungsten filament (straight wire or coiled). The ballast circuitry allows for preheating (up to 1100°C) before the voltage strike. Hot cathode operation allows operation at relatively higher power and over larger tube sizes. In contrast, cold cathode can be a single cylindrical pin electrode at each end. The strike voltage across the electrodes is relatively higher (~10×). The high voltage strips the electrons from the cathode at ambient temperature and initiates the breakdown process of the gas. The coatings on the electrode surface amplify production of secondary electrons, which are produced when high-energy ions and electrons collide against the cathode. These electrons further increase the gas conductivity. Cold cathode fluorescent lamps (CCFL) are compact (~3-mm diameter) and are used in applications such as thin monitors (i.e., LCDs), backlights, timers, photocells, dimmers, closets, and bathrooms. CCFLs are less efficient (<50 lm/W) but provide instant-on and have long lifetimes (50,000 hours). CCFLs operate at high surface temperatures and require complex power supplies which are fairly compact.

The primary functions of the lamp ballast are to provide a high-strike voltage to start the lamp, give regulated current supply during lamp operation and sometimes provide for cathode preheating for rapid restart applications. Often starter circuitry is deployed to preheat the electrodes. It is critical to use the correct lamp-ballast combination for proper operation. Lamp ballast can be a current limiting resistor, magnetic ballast or electronic high-frequency ballast (most modern ballasts). Due to high-frequency operation of electronic ballasts, flicker in fluorescent lamps is reduced to almost unnoticeable. Flicker is caused by fast response of the fluorescent lamps to the voltage fluctuations in the lamp power supply caused by noise or operating power supply frequency.

Lamp failure mode consists of thermionic emission electrode coating degradation (a function of strike voltage and the number of strikes), phosphor degradation, mercury loss (diffusion or absorption by lamp materials) and ballast malfunction. Fluorescent lamps fail to operate far outside the ambient temperature range for which they are designed. Most fluorescent lamps are designed to operate in an ambient temperature of ~20°C. For operation at low temperatures, special cold start circuitry and mercury amalgams are needed.

High-Intensity Discharge (HID) and Low-Pressure Sodium (LPS) Lamps These sources emit light across the spectral line transition of enclosed gases by electrical discharge. The source spectrum also includes background thermal radiation due to the heated electrodes and plasma. These sources are similar to fluorescent sources in basic physics involving discharge and emission of light in the UV and visible due to transitions between the excited states of gas atoms. Unlike fluorescent lamps, the electrodes are separated by less than 1 mm up to a few inches. The enclosed gases are at a pressure that is three orders of magnitude higher than in fluorescent sources. As a result, HID sources are far brighter than fluorescent sources with much higher lumen output. The following types of HID lamps are commonly available: mercury vapor (Hg), metal halides (MH), high-pressure sodium (HPS or nicknamed as White SON), and ceramic metal halides (CMH). CMH combines the advantages of MH and HPS technologies. Each HID lamp technology has very different performance and operating characteristics. An LPS lamp is similar to HID lamps in construction and operation with some differences that are identified as we describe the HID lamps below. Figure 16 describes the construction of various HID and LPS lamps. Figure 17 shows the relative spectrum of various HID lamps and comparison with the fluorescent lamp spectrum.

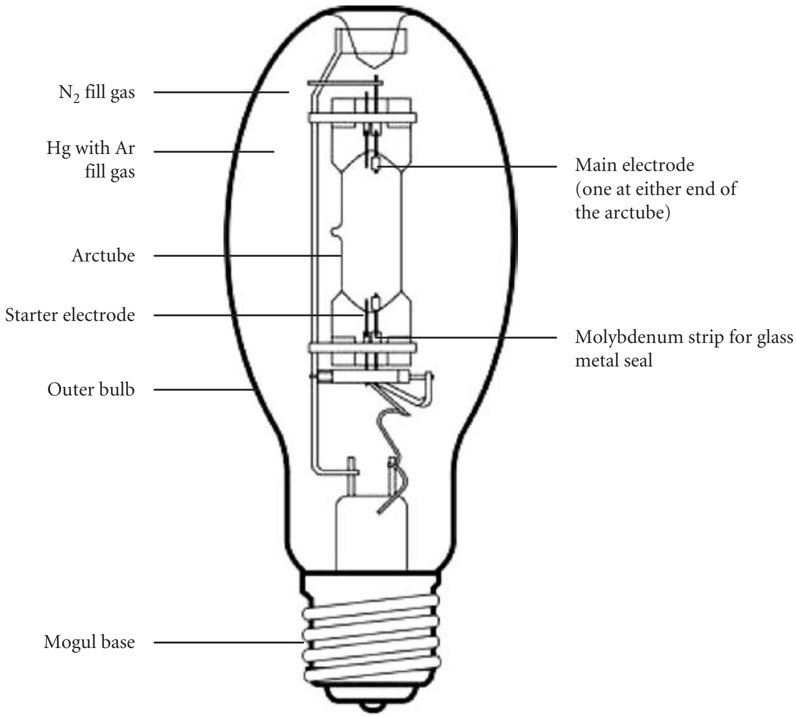


FIGURE 16*a* Mercury lamp construction. (*Illustration courtesy of General Electric Company.*)

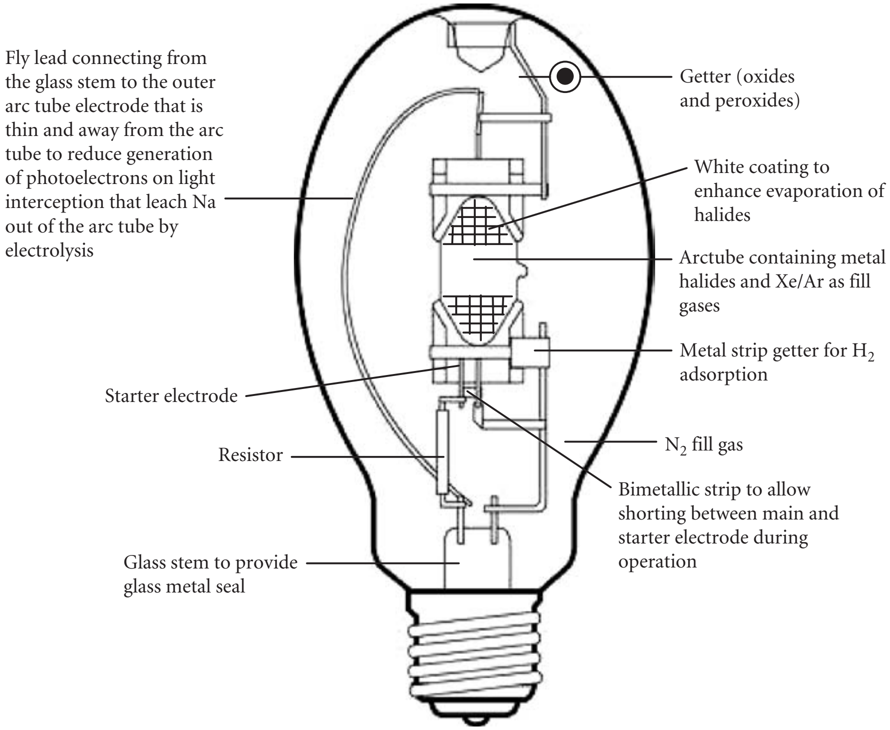


FIGURE 16*b* Mercury halide lamp construction. (*Illustration courtesy of General Electric Company.*)

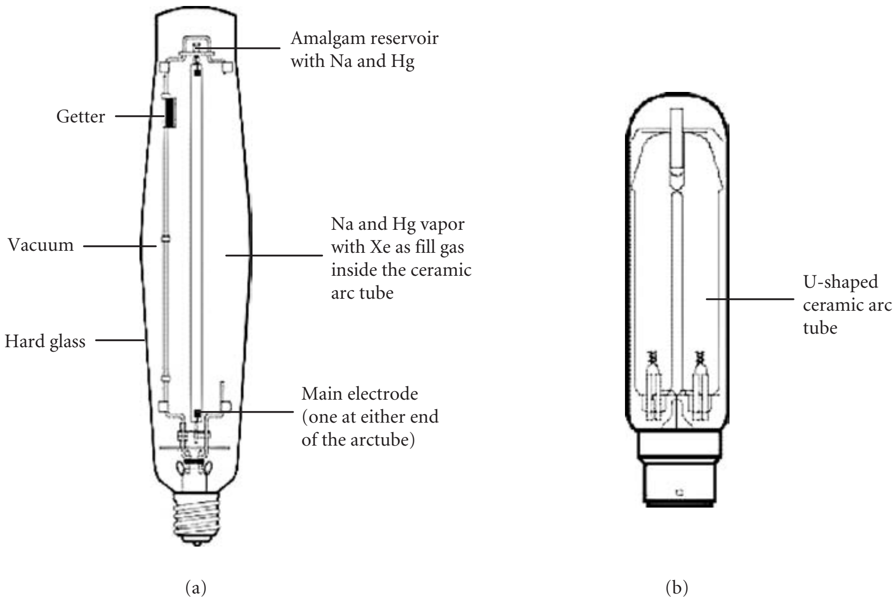


FIGURE 16*c* (*a*) High-pressure sodium lamp construction and (*b*) low-pressure sodium lamp construction. (*Illustration courtesy of General Electric Company.*)

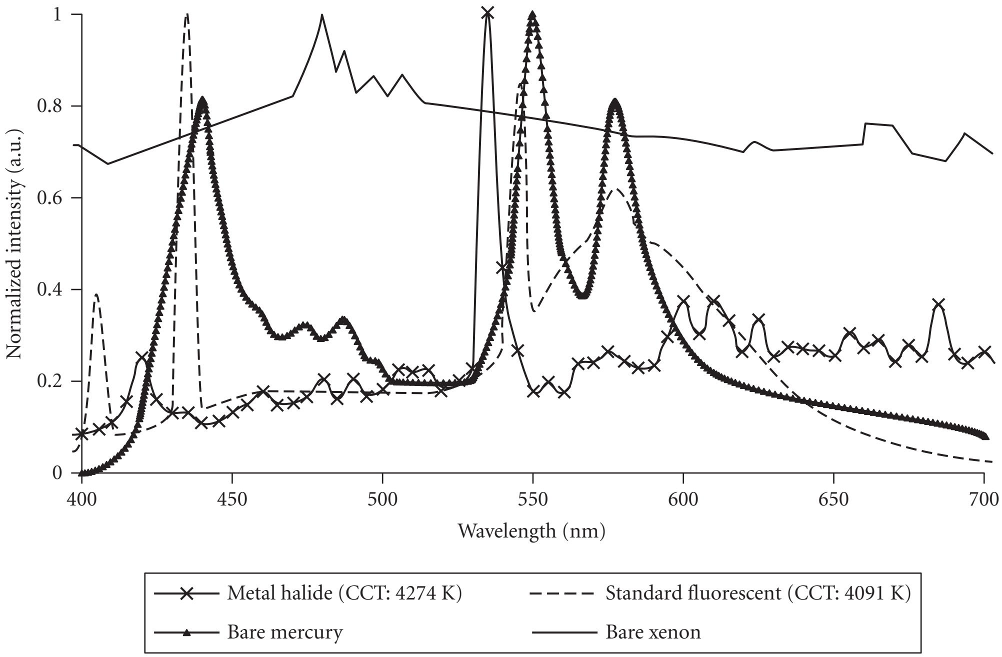


FIGURE 17 Representative lamp spectra of standard fluorescent, bare mercury, bare xenon, and metal halide lamps.

An HID lamp consists of two glass envelopes: inner and outer. The inner glass envelope or the arc tube is made of quartz for MH and Hg and alumina ceramic for HPS, LPS, and CMH lamps. The arc tube houses the discharge gases at high pressure (several atmospheres) and the tungsten electrodes. The outer glass envelope is made of borosilicate and sometimes with soft glass in Hg lamps. It absorbs UV and insulates the arc tube from outer convection currents and from large ambient temperature ranges. It houses the lead-in wires, circuitry to help initiate the high-voltage discharge, getters in case of MH to absorb impurities and has a vacuum (HPS) or low-pressure nitrogen (MH and Hg) to prevent shorting of the lead-in wires. The outer-envelope Hg lamp is sometimes coated with phosphors to provide white light at high CRI and CCT like in regular fluorescent lamps.

Tungsten electrodes are coated with various oxides in a tungsten matrix (except in MH lamps where gases can react with such electrodes) to slow down evaporation and assist in thermionic emission when heated. Starter electrodes, when used in MH and Hg lamps, assist in arc initiation via an electric field between the starter electrode and the adjacent main electrode. During operation the starter electrode is removed from the active circuitry with a bimetallic strip, otherwise premature lamp failure results.

An LPS lamp is similar in construction and operation to HID lamps. Key differences are lower arc tube pressure (0.7 atm), long arc length with a U-shaped arc tube. The arc tube gases include sodium vapor and small amounts of Ne, Ar, or Xe as startup gases.

Different HID lamp types have different gas mixtures. An easily ionizable gas such as Argon (Ar), Neon (Ne), or Xenon (Xe) is used in the arc tube to help in arc initiation. Similarly, mercury is used in most HID lamps to achieve high pressure and improved color rendering. An HPS lamp used sodium (Na)-Hg amalgam. Mercury-free HPS lamps are also available. An LPS lamp uses sodium vapor. The MH lamps use halides of metals in addition to mercury, argon, and xenon.

A low-pressure sodium lamp (LPS) has a CRI of zero due to spectral emission only at 589.0 nm and 589.6 nm (sodium-D line). An HPS lamp has broader spectrum and thus better CRI due to pressure broadening of the sodium-D line. At very high pressures (27 atm), the sodium-D line is self absorbed by the cooler outer layers of the arc leading to a narrow spectral hole around 589 nm. Mercury atoms help in further broadening of the red end of the pressure broadened sodium-D line due to Van Der Walls forces. A CRI from 22 to 85 is achievable depending upon the pressure which can be greater than 90 atm. MH lamps achieve a rich spectrum due to the line spectra of metals like sodium, tin, dysprosium, holmium, thulium, scandium, iron, or cesium. An MH lamp may have mixtures of halides of one or more metals to achieve the desired efficacy, CRI, and CCT.

An MH lamp using a single metal halide compound can also be used to generate discrete spectral output: orange (sodium), green (thallium), blue (indium), and UV (iron). The metal-halide compound is stable at low temperatures and does not react with the arc tube material unlike some metals. At high temperatures, near the arc, the metal-halide compound breaks down and provides the spectral line emission from the metals. The operating temperature is lower than would be the case where the metals are evaporated to see the spectral emission lines. CRI is usually traded for lifetime and efficacy. CMH lamps combine the advantages of MH and HPS by using a poly crystalline alumina as the bulb envelope material. This material does not allow diffusion of metals, especially sodium or reaction of metals with the bulb material. The bulb is operated at a much higher temperature and pressure than the MH lamps. These advantages lead to high color stability with high CRI, uniformity, and efficacy over the lifetime in spite of the bulb material allowing only ~90 percent transmission.

HID lamps require several minutes of start-up time (time to reach stable output) and restrike. A long start-up is due to the time taken to reach a stable operating temperature and pressure within the arc tube. The restrike time interval results from the need to have low pressure inside the arc tube for arc initiation. Complex ballasts are needed to provide startup, restrike, and stable operation with constant current. To improve startup, restrike, and operations at low voltage, a high voltage-low current pulsed start is used. Sometimes, multiple arc tubes within the outer bulb envelope are used to provide faster restrike. Only one arc tube operates at a time in such lamps. Xe-based HID lamps are capable of instant-on and restrike. Automotive HID lamps use Xe with metal halides to improve the start and restrike times dramatically.

The physical orientation of HID lamps such as Hg and MH during operation is far more important than with the other lamps. Due to convection, within and outside the lamp, different portions of any lamp, not just HID, are heated to different temperatures. The lamp engineering must take this into account and ensure that the hottest regions do not constitute a failure mode either by design or by providing instructions to the user for best operating configuration. In MH and Hg HID, the high convection roll within the long arctube has an overwhelming effect on the arc shape and position under gravity. It can make the arc shape curved and lead to nonuniform degradation of the electrode tips and impact the light output, lifetime, and light distribution patterns. HPS lamps, however, can be operated in any position primarily due to a compact arc tube at high gas pressure (5 to 27 atmospheres).

Lamp degradation and failure occur due to electrode degradation by evaporation, arc tube blackening due to electrode material deposition, loss of gas pressure, and selective diffusion of gases leading to change in the lamp color. Arctube blackening also leads to the rise in the arctube temperature leading to an analogous rise in pressure and operating voltage. The effect is especially pronounced in HPS where lamp cycling can occur: as the lamp cools down, it is able to restrike but after some time temperature rises to the point that it shuts down.

Electrodeless Lamps As the name suggests, electrodeless lamps do not have any electrodes internal to the bulb envelope. As a result lifetime is not limited by electrode degradation. The concept behind these sources is over a century old.[48] These sources are being sought to replace conventional light sources where high flux is needed at low operational costs (long lifetimes and high efficiency). There are two kinds of electrodeless lamps: induction lamps (IL) also known as *electrodeless fluorescent lamps* and microwave powered lamps also known as *electrodeless sulfur lamps* (ESL). Extraordinary high bulb life times (>25,000 hours) are possible due to lack of electrodes that degrade under operation. The causes of lamp failure are due to electrical components rather than the bulb itself, which implies a greater lifetime.

In each case, the goal is to excite a discharge with an EM field without the need of electrodes inside the bulb. Alternating magnetic fields in IL or microwaves in ESL initiate the discharge by accelerating the free electrons of a gas with low ionization potential, such as argon or krypton. Free electrons are created in the gas by a spark from a high-voltage pulse across two electrodes in the vicinity of the bulb. These free electrons ionize the gas atoms by impact ionization. Ionization yields more free electrons and ions and the process resumes, eventually resulting in plasma formation. Excited states of gas atoms produce light via spectral transitions across various wavelengths. In case of IL, mercury is present in addition to argon/krypton to produce UV from excited mercury atoms. The UV excites the phosphor coating on the inner surface of the bulb envelope and emits white light just like a regular fluorescent lamp.

In ESL, microwaves are used to produce an intense plasma inside a rotating quartz ball containing argon/krypton and sulfur. The rotation of the quartz ball helps in stabilizing the fill for uniform emission as well as convective cooling with a fan to prevent its meltdown. Initially, the microwaves create a high-pressure (several atmospheres) noble gas plasma. This heats sulfur to a high temperature resulting in brightly emitting plasma. Light emission by sulfur plasma is due to the molecular emission spectra of the sulfur dimer molecules (S_2). The spectrum is continuous across the visible and has >70 percent of its emission in the visible. It peaks at 510 nm, giving a greenish hue. The resultant CRI is 79 at a CCT 6000 K. The lamp spectrum can be modified with additives such as calcium bromide, lithium iodine, or sodium iodide or by using an external color filter.

Electroluminescent Sources Electroluminescent sources are materials that emit light in response to an electric field. Examples of such materials include powdered ZnS doped with copper or silver, thin film ZnS doped with manganese, natural blue diamond (pure diamond with boron as a dopant), III-V semiconductors or inorganic LED materials such as AlGaAs, phosphors coated on a capacitor plane and powered by pulsating current, organic LED (OLED) also known as light-emitting polymer or organic electroluminescent. The sources can operate at low electrical power with simple circuitry.

Electroluminescent sources are commonly used for providing illumination across small regions such as indicator panels. LEDs are already a major lighting source that is rapidly replacing incandescent and fluorescent light sources. The remainder of this section discusses LEDs and OLEDs.

LEDs emit light by electron-hole pair recombination across the P-N junction of a diode. The wavelength of the emitted light corresponds to the band gap (energy gap between valence and conduction bands) across which the electron hole pair is created. The degeneracy in the valence and conduction bands leads to a closely spaced band of wavelengths that constitute light from the LED. Narrow spectral bandwidth enables applications that require saturated colors. Although LEDs are not available for every desired color, it is possible to combine LEDs of different colors to create any color within the color gamut defined by these LEDs. As such, color mixing has become an important field. LEDs emitting in specific bandwidths can be combined with sources with continuous spectra to either enhance a certain spectral region or to provide an easy dynamic color control. One easy method of combining multiple LEDs is using lightguides. Lightguides with rippled surface texture along the cross section are particularly efficient in combining multiple colors with excellent uniformity in a short path length.[49,50]

LED lamps may have an array of small LED chips or a single large chip to achieve the desired power levels. The directionality is controlled by appropriately mounted optics. DC operation of LEDs makes them flicker free sources. Figure 18 shows the structure of a simple packaged LED. Chapter 17 in this volume is dedicated to the subject of LEDs.

LED packages come in various sizes and shapes. Surface mount LEDs (SMD) have minimum packaging and are almost a bare die. LED packages are also offered in multicolored die formats.

Over the years, a variety of materials for LEDs have been used with the goal of obtaining higher efficiencies and different colors across the visible spectrum. LED technology is fast evolving with ever increasing brightness, lifetime, colors, and materials and decreasing costs. The available materials, at the time this chapter was written, are listed in Table 5.

Most lighting applications require white light. Some of the processes for making white-light LEDs are listed below:

- Arrays of small red, green, and blue dies placed in close proximity in a single LED package. Good color mixing takes place in angular space.
- Color-mixing of red, green, and blue colors using lightguide or other optical means.[50,52]

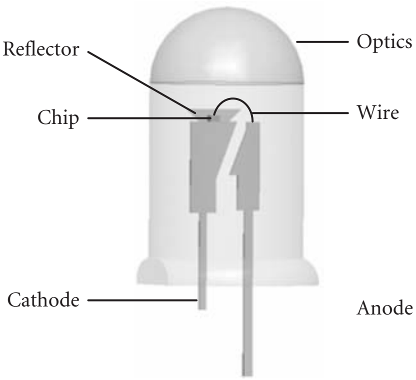


FIGURE 18 Structure of a simple packaged LED.

TABLE 5 LED Materials and Emitted Colors

Material	Color
AlGaAs	red, infra
AlGaP	green
AlGaInP	higher brightness orange, orange-red, yellow, and green
GaAsP	orange, orange-red, orange, and yellow
GaN	green and blue
InGaN	blue (450–470 nm), near UV, bluish-green, and blue
SiC (as substrate)	blue
Si (as substrate)	blue
Sapphire (as substrate)	blue
ZnSe	blue
Diamond	UV
AlN, AlGaN, AlGaInN	UV(<210 nm)[51]
Organic light-emitting diodes (OLED)	Red, green, and blue

- Phosphor excitation by blue or UVEDs.
- Novel techniques like quantum dot blue LEDs or homoepitaxially grown ZnSe blue LEDs on a ZnSe substrate. The active region emits blue light while the substrate emits yellow light.[53,54]

There is a continuous push to improve the LED efficiency and brightness while keeping the lifetimes high. High brightness LEDs became possible due to large area chips, efficient heat extraction and better light extraction from the chip. Internal quantum efficiency of LEDs can be increased by placing emitters inside a cavity[55] to increase the radiative recombination rate. Due to the high internal Fresnel reflections and lateral waveguiding, a lot of light fails to exit the chip. Techniques such as texturing the surface with photonic crystals assist in increasing the light extraction from large dies.[56–58] Figure 19 shows the internal structure of a photonic crystal LED.

Organic LEDs (OLEDs)[59,60] in contrast to inorganic LEDs are size-scalable light sources with richer color spectra. OLEDs can be used to create flexible transparent lighting solutions as they can be printed on a malleable substrate with transparent electrodes. Currently OLEDs are being used for displays and are competing with LCD flat panels. Conceptually, OLEDs are no different from inorganic

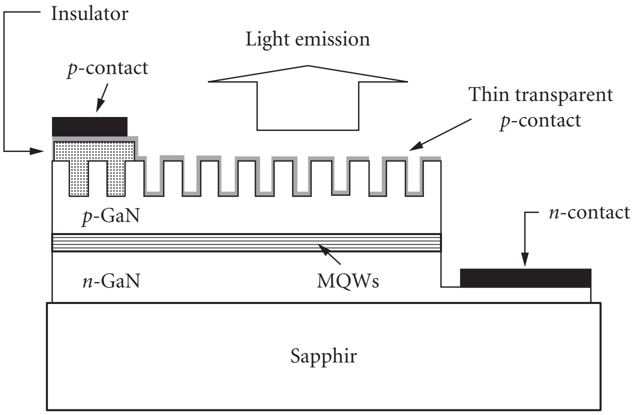


FIGURE 19 Internal Structure of a Photonic Crystal LED. MQW refers to "multiple quantum wells." (*Courtesy: Seoul National University, Korea, http://optics.org/cws/article/research/23635/1/sem_image.*)

semiconductor based LEDs. An OLED deploys layers of organic materials on polymer substrates to form conductive and emissive layers connected to a cathode and anode respectively. Much of the OLED research is aimed at making them brighter and longer lasting.

LED failure causes include damage due to degradation of the active layers with time (spontaneously or in operation); plastic package degradation due to ambient UV; electrostatic discharge; current crowding or inhomogeneous current distribution across the junction leading to hot spots; and thermal stresses causing rupture of the LED package, diffusing of the metal contact material into the die material at high currents, high output leading to facet melting and phosphor degradation in white LEDs, and degradation of organic layers in OLEDs.

Miscellaneous Artificial Light Sources *Neon signs* are essentially cold cathode-like operation of a fluorescent tube without phosphors. A low-pressure mixture of noble gases such as neon, argon, helium, xenon and a small amount of mercury is used in the discharge tube. Neon emits a reddish-orange color; argon emits blue; and krypton, helium, and xenon emit over a wider spectrum. Colored filter glass can be use for making different colors.

Short arc sources function almost identical to HID lamps with the only difference being that the electrodes are much closer (less than 1 mm to 12 mm). The gases are mercury (with argon), mercury-xenon, pure xenon, or metal halides (with mercury and argon). These lamps are primarily used in illuminating high loss systems where the source étendue needs to be as small as possible. Projectors, medical optical instruments, metrology instruments, and daylight or solar simulators use such lamps. These lamps have lifetimes from a few hundred hours up to 10,000 hours. The light sources are typically used with a reflector (parabolic or ellipsoidal). Sometimes the reflector is an integral part of the source/lamp package.

Pure *Xe arc lamps* have an instant-on capability and provide high CRI (>80) at high CCT (>6000 K). Digital cinema projectors and flash tubes (for warning signs, entertainment applications, camera flash lights, and warning or emergency signs and indicators) often deploy pure Xe-arc sources.

Lasers are used for visual displays for entertainment. The subject of Lasers is discussed in Chap. 16 in this volume.

Nuclear sources are self luminous light sources that function by phosphor excitation caused by beta radiation from radioactive materials such as tritium. These light sources are used to illuminate tiny spaces such as watches or displays of instrument panels in very low ambient light.

Glow lamps are low wattage arc sources with gases such as argon emitting in the UV to excite UV-excitable materials or neon to emit orange light to be used as indicator lights.

Carbon arc sources are now obsolete but still find applications in illuminating small areas with bright light under demanding environmental conditions (such as outer space). An arc is struck across a pair of carbon rods and the incandescence from the heated carbon rods provides the light.

Gas lights that operate by the burning of gases like methane, ethylene or hydrogen are used with appropriate lanterns primarily for decorative applications.

Natural Sources: Daylight Daylight can be utilized in the lighting design of buildings to provide a pleasing environment that enhances physiological well-being and productivity and also energy savings during the day by reducing the need for artificial lighting and solar influx contribution to building heating. Daylight is primarily used for ambient lighting. It can be used for task lighting when integrated with electrical lighting. Daylight constitutes direct sunlight, scattered sunlight from the atmosphere, reflected sunlight from the clouds, and reflected light from the surroundings such as ground (especially snow) and objects such as buildings. The solar spectrum changes with atmospheric conditions and so does scattered light from the sky or reflected light from the ground. The CCT of Sun is 1000 to 5500 K, clear blue sky is 10000 to 100000 K, overcast sky is 4500 to 7000 K and clear sky with sunlight is 5000 to 7000 K. Figure 20 shows an example of the solar spectrum at the ground, at noon, at Golden, Colorado. Note the IR content in the spectrum and the shift in spectrum from noon to evening.

Designing for daylight requires close attention to many factors:

- Goals of providing daylight: physiological well being of occupants and/or energy savings.
- Intended distribution of light inside the building during the day and in the night. Penetration of daylight into the interiors and the impact of reflectivity from various surfaces.
- Impact of daylight on materials such as wall paints, artwork, plastic materials, furniture, and plants. The UV component of daylight is generally harmful to most materials via solarization of plastics or fading of paints and stains. If the impact of UV is not known and acceptable, then the UV should be rejected by the optical system components through coatings or materials.
- Integration of daylighting-based building design with other controls such as for electrical lighting, cooling and any automated systems.

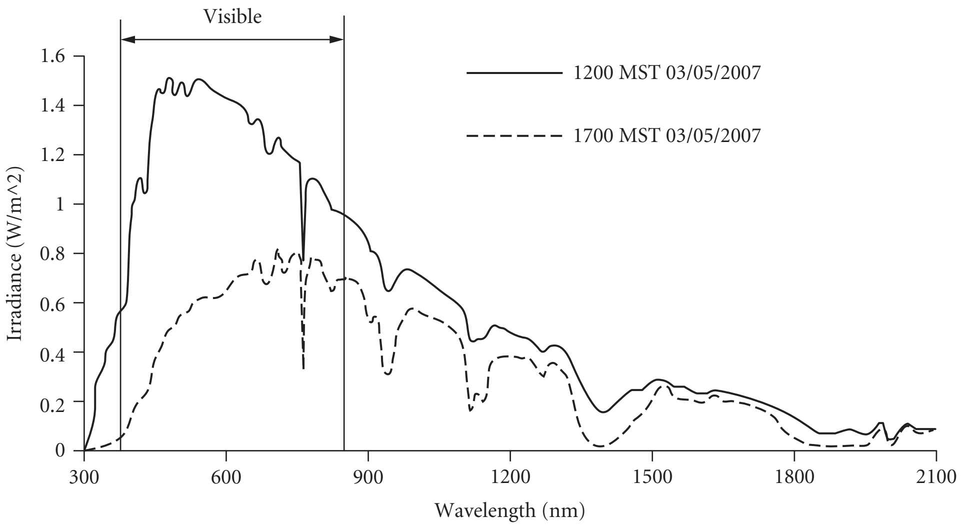


FIGURE 20 Solar spectrum recorded at ground at Golden, Colorado at two different times during the day. (*Courtesy of National Renewable Energy Laboratory, USA.*)

- Location (latitude and longitude) and orientation of the building relative to the surroundings. Simulating the daylight entering the building during various times of the day and the year.
- Design for reduction or elimination of glare from daylight sources. Internal layout of the building during intended use will play a key role.
- Outside view requirements via windows. A minimum window size[61–63] is needed for a given geographic location, and a certain window location is dictated by aesthetic reasons including the desired view from the window. The minimum window size can also depend upon the prevalent building regulations based on wall size or floor size. Under such circumstances, the daylight entering must be controlled or balanced with interior lighting and cooling for uniformity, glare, and heat management. Daylight can be controlled by providing appropriate window shades, glazings, or even additional windows or skylights at appropriate places.

It is not always possible to obtain energy savings with daylight due to increased heat load, especially during summers and the need to supplement daylight with electrical lighting during the night. Infrared rejection is achieved by using special glazings. To limit glare, glazing such as high reflectance, low transmittance, electrically controlled transmission, tilted glazings with angularly dependent transmittance or IR reflecting films are used. Adequate consideration must be given to the window view impact due to any of the daylight control mechanisms. A very low-transmittance glazing can make the outside view appear gloomy on a bright day.

Luminaire Design

The source is the starting point of the luminaire design. The optics performs at a minimum two functions: first to capture the light from source and second to transfer light efficiently to the desired distribution at the target (i.e., illuminance, intensity, and/or luminance). The choice of the optics is also a challenging process. First, the designer must select if refractive, reflective, or both types of optics (i.e., hybrid) are to be used in the design. Reflective optics have been a standard for most sources, with flat refractive optics used at the output aperture in order to protect the other optics. Until recently reflectors were standard conics such as ellipses, hyperbolas, parabolas, or spheres. Standard refractors in use include cover plates (still called a lens), pillow lens arrays, Fresnel lenses, and other faceted designs. However, with advances in LEDs, refractive optics are increasingly being used for advanced function. Solid-state lighting optics are either plastic or glass that surround individual or a limited number of LEDs. They are hybrid optics that use at least total internal reflection (TIR) and refraction at the input and output facets, but they can also use reflection, scattering, and even diffraction. With the advent of better technology, especially manufacturing capabilities and software for modeling, faceted and continuously smooth surfaces parameterized with nonuniform rational B-splines (NURBS) are being developed. For high-performance, injection molding of plastic or glass is being increasingly used. For refractive optics, the surfaces are left bare, but for reflective optics there is vacuum metallization of the surfaces. Reflectors are also made with stamping methods, but these optics tend to have lower performance.

Baffles (louvers) are often considered by many to be optics of the system; however, many, rather than shaping a distribution through redirection of the light, block or even absorb incident radiation. Thus, while some baffles are reflective and provide some shaping of the illumination distribution, they most often achieve shaping through subtraction rather than addition. They are primarily added to alleviate glare, trespass, and pollution, but they are also included for aesthetic reasons, correcting errors in the design process, and to hide structure within the luminaire.

The source coupling aspect is the focus of the next section, following that is a discussion of the design of the optics and subsections on baffling in the form of luminaire cutoff classification and types of luminaires. Following this process from the source to the optics to the baffle to the target, while always considering the perception aspects of the illumination (see Sec. 40.3), means that aesthetically pleasing while technically sound lighting can be developed.

Étendue and Source Coupling For reflective optics, the source-coupling components also act as the transfer optics, often in conjunction with a front, protective lens. With the advances in source technology that use hybrid, dielectric components, coupling of the sources, is increasingly important in order to improve upon system efficiency. Typically, individual LEDs are placed in recesses in the dielectric optic, and by obeying the conditions for TIR, all of the emitted light can be captured by the coupler and then transferred to following optics that shape the emitted distribution.

In all cases, the term étendue describes the flux transfer characteristics of the optics, starting with the coupling optics, of an optical system, such as a luminaire. Étendue is a geometrical quantity that is the integrated product of an area and solid angle. In paraxial form it is the Lagrange Invariant, but in nonparaxial form it is given by

$$\mathscr{E} = n^2 \iint_{\text{pupil}} \cos\theta \, dA \, d\Omega \tag{12}$$

where $\mathscr{E}$ is the étendue, dA is the differential area, $d\Omega$ is the differential solid angle, θ is the angle with respect to the surface of interest (i.e., normal), and n is the index of refraction of the space. The limits of integration in area are over some aperture (e.g., a lens clear aperture or a reflector exit aperture), while the solid angle integration is over the limits that are passed by the aperture. For example, consider a source of area A_s that emits into a half angle of θ_0 from every point on the surface. The étendue for this source is

$$\mathscr{E} = n^2 A_s \int_0^{2\pi} \int_0^{\theta_0} \cos\theta \sin\theta \, d\theta \, d\phi = \pi n^2 A_s \sin^2\theta_0 \tag{13}$$

In lossless optical systems, étendue is conserved. Thus, in order to design the most efficient luminaire, one must continue to match the étendue as one progresses through the optical components of the system. For example, if the source of Eq. (13) is used for a luminaire, one must keep this étendue quantity consistent. If one desires to reduce the angular spread of the output from an optic ($\theta_0 > \theta_{\text{optic}}$), then the area of the optic must be increased ($A_s < A_{\text{optic}}$). The counter also holds true: to reduce the real extent ($A_s > A_{\text{optic}}$), one must increase the angle ($\theta_0 < \theta_{\text{optic}}$). An expression for conservation of étendue in a generalized form is

$$dx\,dy\,dp\,dq = dx'\,dy'\,dp'\,dq' \tag{14}$$

where the dx and dy terms are the differential position terms and the dp and dq terms are the differential optical direction cosine terms, which are equivalent to ndL and ndM respectively. More information about étendue can be found in Chap. 39, "Nonimaging Optics: Concentration and Illumination," in this volume. Another factor related to étendue through a differential is skewness, which denotes the twist on individual rays of light in an optical system. Skewness is also invariant and implies that transfer from one source geometry (e.g., a square) cannot be transformed to another source geometry (e.g., a circle) without loss except if some rotational asymmetry is added to the optical system. Further information about étendue and associated terms like skewness can be found in the literature.[64]

Luminaire Design Methods There are a multitude of design principles for the design of the optics of a luminaire. Fundamentally, most design methods are based on the basic conic shapes as listed in Table 6. Each of these shapes provides a basic intensity distribution at its output aperture. However, increasing demands of tailored light distributions and also increased efficiency require perturbations to these basic design forms. Furthermore, the topics of light trespass, light pollution, and glare are receiving a wealth of attention from ordinance and regulatory agencies. To reduce glare issues it is best to use diffuse optics with a well-defined cutoff. In the field of nonimaging optics (see Chap. 39), the edge-ray theorem provides a means to have a well delineated cutoff. The edge ray is defined by the maximum extent of the source, thus providing a maximum cone of light from the reflector designed around the source shape. However, the edge-ray principle is passive with respect to the luminance distribution of the source—it contends for the maximum extents but not the physical distribution of light in the radiation pattern.

Thus, tailoring methods have been developed. The tailoring methods specify the shape of the optics based upon the luminance distribution of the source and the desired illumination pattern

TABLE 6 Basic Conic Shapes, Their Conic Provide at Their Output Aperture Constant, and the Basic Intensity Distribution That They Provide at Their Output Aperture

Shape	Conic Constant (k)	Base Intensity Distribution
Hyperbolic	k <−1	Diverging; far-field applications
Parabolic	k = −1	Collimating; pseudocollimation applications
Elliptic	−1 <k<0	Converging; near-field applications
Spheric	k = 0	Converging; self-imaging applications

(i.e., luminance, illuminance, and/or intensity) at the target. These methods are extensive and beyond the confines of this chapter. The reader is encouraged to consult the *Handbook* chapter on nonimaging optics (Chap. 39) for a brief introduction, the theoretical book on nonimaging optics by Winston, Miñano, and Benítez,[64] and the applied book on nonimaging optics by Chaves.[65]

Luminaire Cutoff Classification A cutoff ensures that light from the luminaire is restricted above the horizon with respect to the lamp geometry. Cutoff is designed into the luminaire through the optics (i.e., edge-ray designs) and/or the integration of baffles. While most applications do not require cutoff classification, except for those used on the exterior, such as automotive, roadway, and landscape lighting, most designers include such to make effective lighting systems by alleviating potential glare, trespass, and pollution concerns. Often strict cutoff guidelines are mandated by governmental standards, such as for automotive, traffic signal, and roadway lighting. The goals are to provide the required lighting level to its users, while also alleviating light pollution and light trespass. Light pollution is light that is directed up into the atmosphere, causing sky glow, which is especially present in urban settings. The reduction of light pollution is a growing trend being addressed by the astronomy community. When light is incident on surfaces outside the intended illumination region, it is called *light trespass*. The impact of light trespass from roadway lighting is a major concern in residential areas.

For both trespass and pollution the luminaire cutoffs provide a protocol to reduce both. Automotive lighting does not use the criteria presented here, but rather use a set of governmental standards. Roadway and external lighting make the most use cutoff criteria as shown in Table 7. See Fig. 22 for a depiction of the angles listed in Table 7.[66]

Luminaire Classification System In 2007 the IESNA published research results for refinement of the cutoff classification system of the previous section.[67] This study focused on light distribution in front of the luminaire (forward light), behind the luminaire (back light), and above the luminaire (uplight) as shown in Fig. 21. They found the photometric luminaire efficiency ($\eta_{\text{luminaire}}$) to be

$$\eta_{\text{luminaire}} = 100\frac{\Phi_{\text{forward}} + \Phi_{\text{back}} + \Phi_{\text{uplight}}}{\Phi_{\text{source}}} \tag{15}$$

where Φ_{forward}, Φ_{back}, Φ_{uplight}, and Φ_{source} are the integrated fluxes in lumens over the solid angles shown in Fig. 21 for forward light, back light, uplight, and the bare source, respectively.

TABLE 7 Amount of Emitted Light Criteria for the Luminaire Cutoff Classification[66]

Type	Horizon and above (90° and greater)	10° below Horizon (80° to 90°)	Remainder (0° to 80°)
Full Cutoff	0%	≤10%	≥90%
Cutoff	<2.5%	≤10%	≥87.5%
Semicutoff	<5%	≤20%	≥75%
Noncutoff	No restrictions over entire angular space		

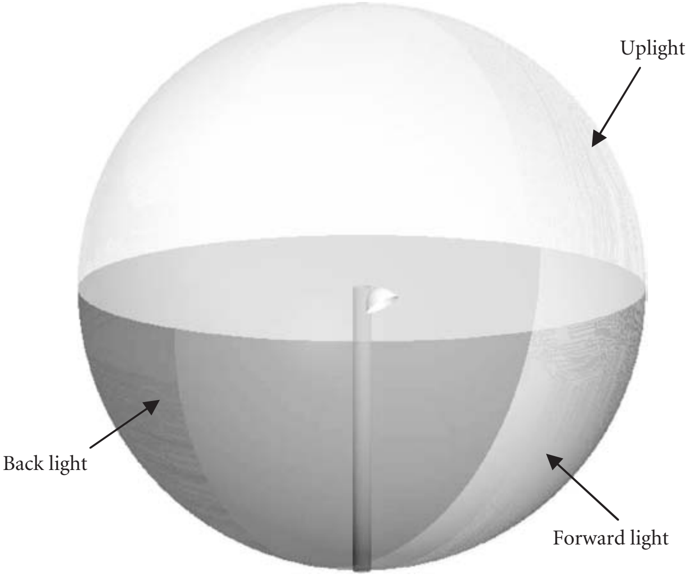


FIGURE 21 Lighting classification system zones for forward light, back light, and uplight based upon the exit aperture of the luminaire.

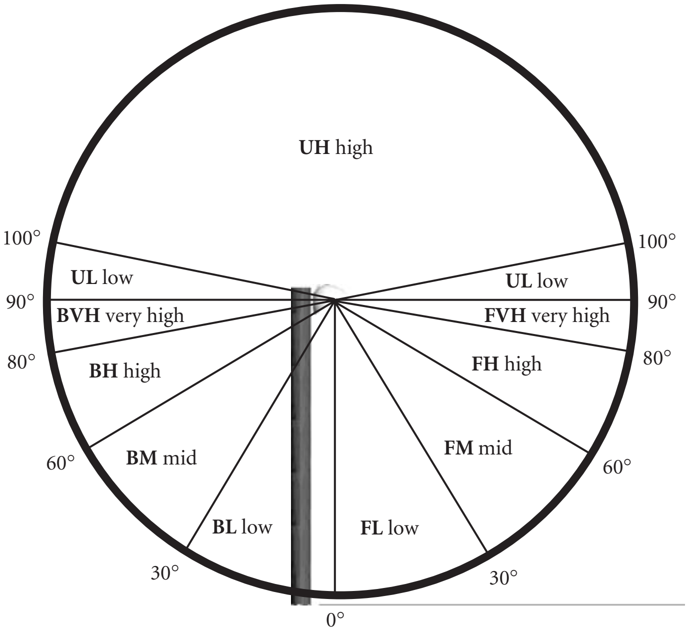


FIGURE 22 Layout of the light classification system subzones. (See also color insert.)

These three zones are then broken down into a total of 10 subzones as shown in Fig. 22. The lumens in each subzone is measured with respect to the bare source flux, as in Eq. (15), in each of these subzones and then reported as an evaluation of the luminaire. These subzones indicate the distribution of light over several regions rather than restricted to the 80° and greater as per the previous section. Standard goals include reduction of light above the horizon (i.e., all uplight subzones and the BVH and FVH subzones) and the desired uniformity over the other zones. This new classification system provides for better control of the illumination such that both vertical and horizontal surface illuminances can be addressed in the design process. Horizontal surface illuminance criteria are met by increasing the flux in the BM to FM subzones. Vertical surface illuminance criteria are met by increasing the flux in the BM, BH, FM, and FH subzones.

Luminaire Optics There are innumerable schemes to the design and availability of luminaire optics, both for artificial and natural sources. Methods employing reflectors, refractors, TIR optics, and combinations thereof have been developed. Additionally, the optics are both specular and diffuse or a combination of these two are used. In the next few subsections, we provide examples of commonly available luminaire optics. Finally, as per Table 6, the shapes of the optics are typically based on conic shapes.

Luminaire optics for artificial sources While the design of the optics of the luminaire is to provide a desired illumination distribution, we learned from the previous sections that light cutoff is important in the design of the luminaire. In fact, the ability to hide or shield the source from direct view in order to reduce glare concerns is as equally important as obtaining the desired illumination distribution. A reflector as shown in Fig. 23*a* has a fairly wide direct view of the source, denoted as the shielding angle or similarly the cutoff angle. Room lamps are perfect examples of this dual requirement since it is typical to use a diffuse shade around the source. The source and shade (which also acts as a diffuse reflector) provide the desired general illumination, while the shade provides the requisite cutoff. Besides using the body of the reflector to hide the direct view of the source, louvers or baffles (see Fig. 23*b*), a prismatic or Fresnel lens (see Fig. 23*c*), or a bulb shield (see Fig. 23*d*) are

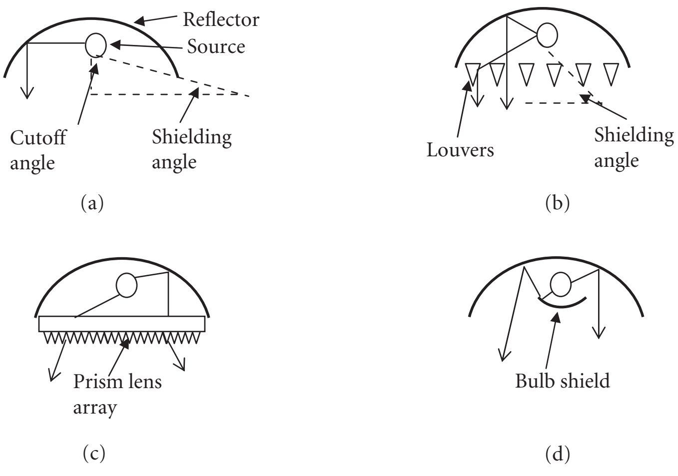


FIGURE 23 Glare issues of four luminaire geometries: (*a*) the reflector providing the cutoff; (*b*) louvers, flat or parabolic, increasing the shielding angle; (*c*) a lens array, prismatic or Fresnel, which directs more of the light emission downward thus reducing the direct intensity level of the source; and (*d*) the inclusion of a bulb shield to ensure that all emission strikes the primary reflector at least once. (*Adapted from Ref. 5, p. 71.*)

added to the luminaire. For the baffle case two standard options are typically used: vertical, strongly absorbing louvers, or specular reflecting parabolic louvers. The former inhibits direct view of the source in the luminaire while also absorbing the glare-inducing light. The latter also reduces the direct view angle of the source, but it uses the parabolic, specular louvers to direct the glare-producing light into directed radiation typically outside the direct view of an observer. The lens, prismatic or Fresnel, coupled to a reflector causes most of the emission to be directed downward, thus frustrating the direct imaging of the source. This obscuration of the source means glare effects are reduced. The bulb shield, which is typically spherical, ensures that all light from the source is incident on the primary reflector of the luminaire, thus completely hiding the source from direct view and in turn greatly reducing the glare potential.

The specifics of the lamp design depend on the application. Figure 24 shows some representative luminaire designs. Figure 24*a* shows a banker's desk lamp, which has multiple bounces within the glass envelope optic. It creates a wide illumination distribution, but the colored glass and the multiple bounces softens the appearance of the bulb located within. The envelope optic can be positioned by the user to alleviate source glare while also providing the desired illumination over a desk surface. Figure 24*b* shows a Bouillotte table lamp, which uses two vertically oriented fluorescent lamps. The shade hides part of the bulbs from direct view, and the coating on the fluorescent tubes causes near-Lambertian emission; therefore, the illumination for this lamp is wide and glare issues are minimal. Figure 24*c* shows an indirect RLM lamp fixture that is suspended from a ceiling. The indirect nature

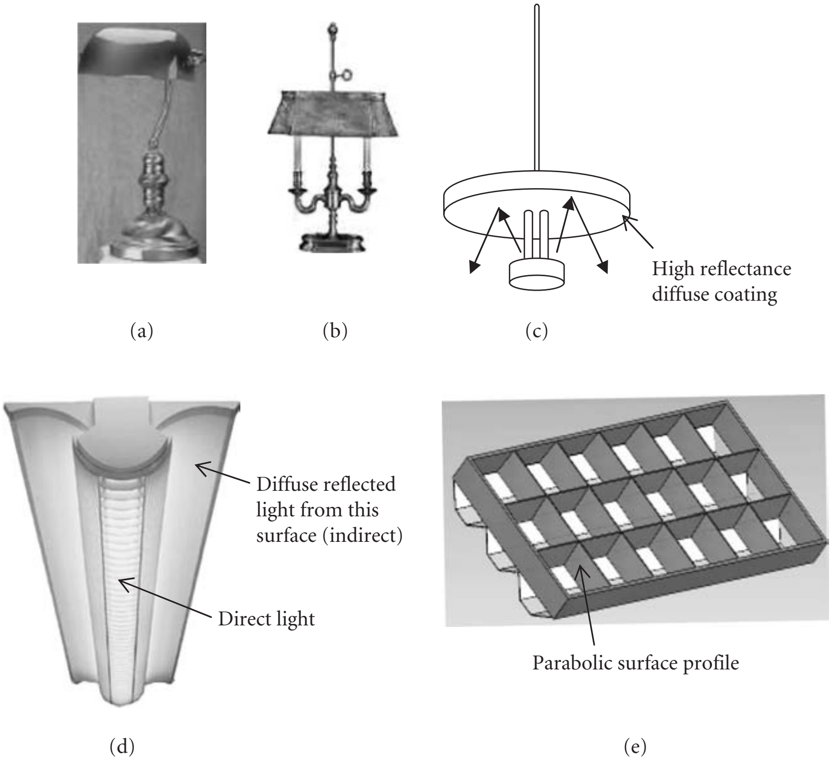


FIGURE 24 Depictions of luminaires: (*a*) Bankers lamp: multiple bounces inside the reflector create a wide angled uniform illumination; (*b*) Bouillotte lamp: vertical fluorescent tubes provide diffuse illumination; (*c*) indirect lighting with RLM fixture where the top surface reflects light into a wide angular range; (*d*) overhead direct-indirect lighting fixture using fluorescent tubular bulbs; and (*e*) parabolic louvered trough reflector for fluorescent tubes. (See also color insert.)

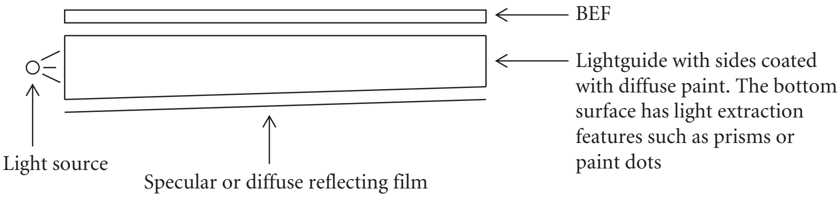


FIGURE 25 An edge lit backlight. (BEF: Brightness enhancing films.)

is due to the inclusion of a bulb shield and a highly reflective diffuse primary reflector thus alleviating glare. Figure 24*d* depicts a direct-indirect overhead, fluorescent lamp fixture. The white, diffuse wing structures provide indirect lighting, while the central section is louvered direct lighting. The direct lighting provides task illumination needs, while the indirect lighting provides a general light level for the room. Finally, Fig. 24*e* shows a standard overhead office luminaire: a series of parabolic troughs (called a troffer) in which long, tubular fluorescent lamps are located. The parabolic louvers reduce glare concerns by increasing the shielding angle, while also increasing the task illumination due to the specular reflectivity of the vanes. Instead of using the louvers, a pillow lens array or prismatic lens can be used; however, computer monitor glare issues can arise with these lenses. Other luminaire geometries not presented here include track lighting, recessed lights, chandeliers, and spot lamps. Please see Refs. 71 and 5 for more information.

Backlighting Backlighting is used extensively in photography to separate the background from the subject and create 3D effects. It can be used for the same purpose in interior lighting to illuminate displays from behind. Backlighting is used extensively in signage, to illuminate instrument panels and device display panels such as laptop and cellphone screens. A typical edge lit backlight operation is illustrated in Fig. 25. Light enters the planar lightguide[68] (for example, 50 mm × 50 mm × 5 mm) from the thin edges and bounces around. Carefully designed and positioned light extraction features such as prism or spheres deflect the light out of the lightguide. As a result the entire planar surface is lit and appears as a planar light source. Modern backlights use sources such as CCFLs and LEDs. With LEDs, dynamic multicolored backlit displays are possible as lightguides allow for efficient color mixing. Edge lit backlighting can be used in direct lighting of large spaces such as living rooms by creating illuminated ceilings, walls, or artificial windows. Figure 26 shows one such application where backlit ceiling tiles are used to create an illuminated ceiling or an artificial skylight. A picture of sky and vegetation is superimposed on the tiles to create an effect of natural sky with vegetation on the roof. Backlights could be replaced by OLEDs which provide not only illumination but also information content.

Luminaire optics for daylight sources Daylighting schemes[69,70] involve careful layout of windows, skylights, skytubes, and controls such as shades, window overhangs, window depths, light shelves, and hybrids with electrical lighting. For effective daylight illumination, it is necessary to determine the access to sunlight by taking into account the sun path across the sky during the day and across different months and the impact of neighboring buildings and ground features. Daylight can be used for city lighting too with careful planning. Heliostats or large plane mirrors have been used atop buildings or even mountains to direct sunlight into the city interior.

Layout of windows and skylights can utilize schemes such as side lighting, top-level lighting, and clerestory lighting. Placement of nonview providing windows for providing daylight must be designed carefully for maximum daylight penetration and controlled glare. Side lighting allows daylight in from the walls usually at eye level, top lighting allows daylight in from skylights, and clerestory lighting allows daylight in from the side windows near the roof above the eye level. Clerestory windows provide more uniform ambient illumination over a larger region. However, proper attention must be given to glare from the sky or direct sun by using baffles. The depth of windows near the ceilings or window overhangs also helps in limiting such glare. Figure 27 shows several different

FIGURE 26 A conference room with artificial skylight made up of backlit ceiling image tiles. (See also color insert.) (*Courtesy of The Sky Factory, LLC.*)

layouts of windows and skylights that bring daylight into the interiors. [71,72] The location and number of openings for daylight determine the penetration and uniformity of the illumination achieved. The height and the slope of the ceilings determine the penetration and the illumination gradient achieved inside the room. For example, for daylight from windows located near the ground, having a tall ceiling allows light to penetrate to the farthest ends of the room. Similarly a sloping ceiling with windows located near the ground allows a gentler illumination gradient from the window to interior.

The reflective properties of the walls and the ceiling must be taken into consideration when simulating the impact of daylight. High reflectance paints on the ceiling can be used to spread the daylight entering from the window portion near the ceiling into the building interiors. Window blinds, shades, and mechanical louvers are commonly used to control daylight. Sometimes partition walls around certain window sections are used to control glare or even limit the extent of illuminated region such as artwork in museums.

Light shelves are used interior or exterior to the windows to allow daylight from the sky in without glare. Light shelves consist of large horizontal sections hanging below the top edge of the window. A layout of mirrors or even just a plane aluminum sheet directs the daylight from the sky toward the ceiling or deep into the room without hitting the ground. A reflective ceiling will scatter daylight into the room. Combinations and variations of these schemes can be used to suit a particular situation. Figure 28 illustrates the concept of light shelves. Suncatchers are similar in concept as shown in Fig. 29.

Skytubes are lightguides that carry daylight into the building interiors. The inside walls are specular with high reflectance. These tubes may be straight or curved, as needed, to transport daylight to different regions. Curved lightguides have a symmetric cross section to maximize light transfer efficacy across the bends.

Hybrid daylighting systems consist of daylight integrated with electrical light as shown in Fig. 30.

Solar lighting systems include the use of tracked or untracked mirrors, lenses or apertures for collecting sunlight and channeling it into the building interior via skytubes, lightguides or fiber-optical cables. Heliostats or large plane mirrors are used at locations with access to the Sun and they direct that light into building interiors or even city interiors. Optimally, these mirrors track the Sun.

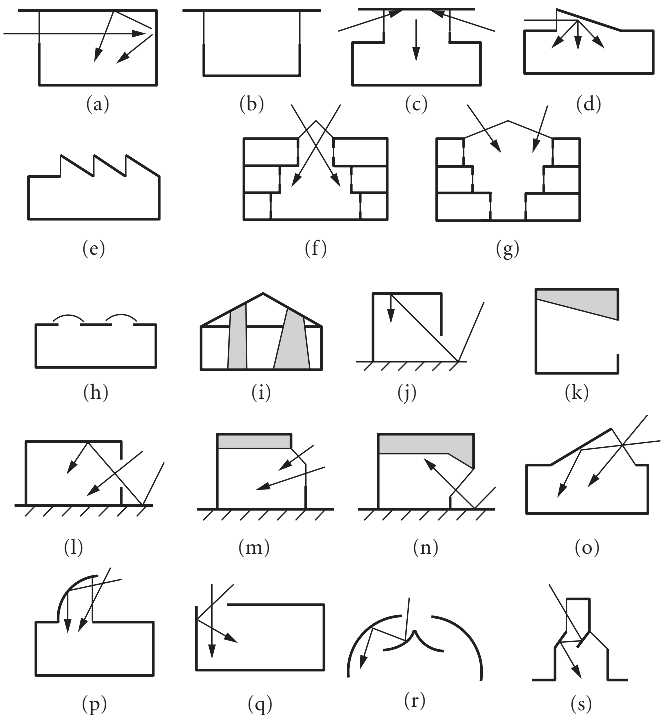


FIGURE 27 Windows for gathering daylight: (*a*) Unilateral, side lighting. (*b*) Bilateral, side lighting (*c*) Roof monitoring. (*d*) Clerestory. (*e*) Sawtooth skylighting. (*f*) Atrium. (*g*) Litrium. As opposed to atrium it provides best light distribution to adjacent spaces. (*h*) Top skylighting. (*i*) Skywells: straight and splayed sections. Shaded region shows the lit region. Splayed section distributes light farther, more evenly and with reduced peak brightness. (*j*) Window near the ground. Deep ceiling allow deeper light penetration. (*k*) Tilted ceiling reduced the illumination gradient from the window to interior. (*l*) Window in the mid-section allows direct skylight and ground reflected skylight. (*m*) "Greenhouse" opening for overcast sky. (*n*) "Overbite" opening for ground reflected skylight. (*o*) Tilted glazing with clerestory opening to allow sunlight from a wider range of elevations. (*p*) Capturing daylight via top lighting. (*q*) Using high reflectance wall adjacent to top lighting to provide glare free light. (*r*) and (*s*) Top lighting via lightguiding.

Figure 31 shows use of a solar light pipe (SLP) to bring sunlight deep into the building interior. The atrium is 140 ft deep, 60 ft long, and 9 ft across. Without the SLP, the view in the building interior was a dark concrete wall. A rooftop heliostat captures sunlight and directs in down into a prismatic glass cone. The glass refracts the incoming sunlight horizontally onto an outboard cylinder of open weave fabric; creating a glowing, translucent, 120-ft-long tube of diffuse sunlight. This display is visible from the 14 floors of atrium offices and also from the ground floor lobby, elevator lobbies, and the library. The SLP projects a 10-in diameter sunburst onto the lobby floor (Fig. 31*b*). Besides injecting daylight into dark spaces, the SLP's unique design provides a compelling and a very dynamic visual focus for the atrium occupants. It constantly updates their understanding of the Sun, the sky, and the weather patterns and reconnects them to the otherwise solar rhythms of the day and seasons. At night, powerful searchlights use the "at rest" heliostat and SLP to inject a shifting palette of colored light into atrium.

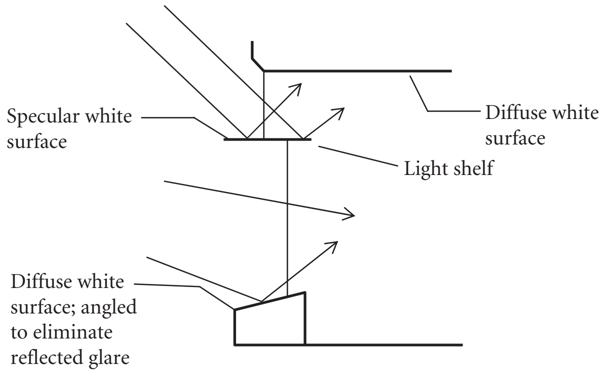


FIGURE 28 Light shelf to limit glare from direct skylight and redirect light to the ceiling.[72] The light shelf can be curved in shape and moveable angularly. The position of the light shelf relative to the window can be interior, exterior, or both. Exterior light shelf provides shading while interior light shelf limits glare. Blinds or moveable shades can further help in glare control.

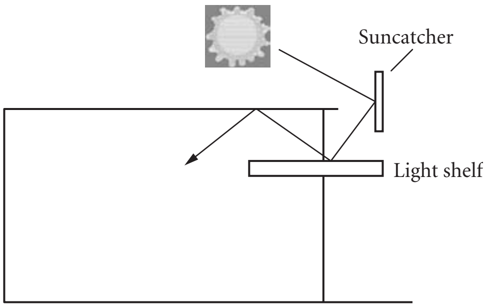


FIGURE 29 The concept of suncatcher. The surfaces of suncatcher and light shelf are of high reflectance specular or diffuse finish. Light shelf is optional. Suncatcher reduces the view, eliminates direct glare and increased illumination when the sun is at a particular location.

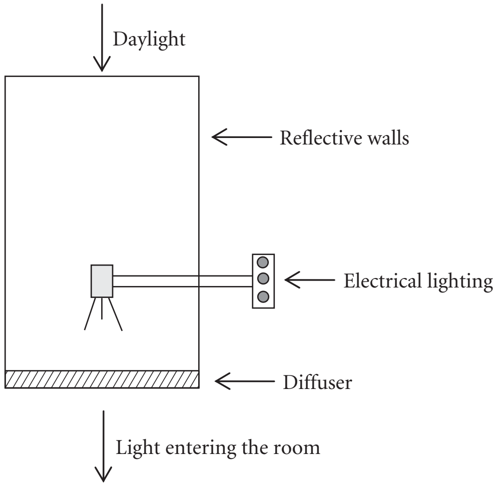


FIGURE 30 A skytube or skywell with integrated Daylight and electrical light.

The use of modern CAD software, especially radiosity based, makes it easy simulate the daylight (that includes sun-tracking, scattered and reflected light from the sky, ground, and neighboring buildings throughout the day and the year), its interaction with optical components such as optical fibers, lightguides, lenses, and diffusers; its penetration through the windows into the interior; impact of reflection from walls, ceilings or furniture, and interaction with interior lighting.

(a) (b)

FIGURE 31 A Solar light pipe. (*a*) A 140-ft-tall light gathering and distributing device that presents daylight down into the core of a building that has no other access to daylight. (*b*) Light projected (10-in diameter) on the floor. (See also color insert.) (*Photograph by Paul Warchol; Courtesy of Carpenter Norris Consulting.*)

40.6 LIGHTING MEASUREMENTS

In this section, we discuss briefly the tools and techniques used for measuring light, 3D object profiles and optical properties of objects, in the context of lighting applications. The quantities most relevant for light measurement are horizontal/vertical illuminance and luminance of lamps and lit objects as a function of wavelength. To measure the optical properties of objects, luminance measurements in transmission and reflection as a function of wavelength, magnitude, angle of viewing, and direction and angle of incident light are needed. To model the objects in CAD software, measurement of 3D object profiles is needed. These measurements help in picking the lamps and their placement geometry to achieve desired lighting goals.

For measuring light from the source, we discuss the following instruments: illuminance meters and goniometers. For measuring the optical properties of objects, including luminaire optics, in reflection or in transmission, we discuss instruments such as reflectometers and luminance meters. For the measurement of luminaires conformance to the design, we present two methods: CMM and laser scanning.

Illuminance Meters

Illuminance meters or luxmeters measure illuminance in lumens/area. These are typically handheld devices, as shown in Fig. 32 that consist of a photodiode with a photopic correction filter and a cosine corrector on top of it. The photopic correction filter multiplies the incident light spectrum by the eye's photopic response to convert the incident energy in watts into lumens. The cosine corrector consists of a diffuser such as a plastic disk or flashed opal disk or a small integrating sphere with a knife edge entrance port. The goal of the diffuser is to provide a constant relative distribution of angles to the detector regardless of the incident angle of light on the diffuser. High Fresnel losses at high angles of incidence at the surface of the diffusers such as plastic disk or opal glass can still introduce errors. These errors can be minimized by allowing some light to leak through the edges of the diffuser and then using a screening ring to prevent additional error due to leaked light.[73]

(a) (b) (c)

FIGURE 32 Handheld lighting measurement instruments. (*a*) Simple Luxmeter; (*b*) Luxmeter (*from Labsphere*) with an integrating sphere as a diffuser; and (*c*) luminance meter (*from Konica Minolta*).

Luminance Meters

Luminance meters measure luminance in lumen/area/solid angle. These are handheld instruments (Fig. 32) and are equivalent to using a lens and placing a luminance meter at the image location of the image formed by the lens of the target object. Thus it consists of a detector, a photopic correction filter or a color filter, a cosine corrector and an imaging lens. The lens is used to image the region of the object to be measured on the entrance to the detector (or the cosine corrector surface). Since the NA of the lens is known, the solid angle is known. This allows us to obtain the luminance by dividing the detected illuminance by the solid angle. Care must be taken to focus the lens only on the region whose average luminance has to be evaluated. Apertures with different field of view are provided to limit the region over which luminance is evaluated.

These instruments can be made more sophisticated by using a high-quality CCD detector array to image an entire scene and provide luminance distribution across it. The imaging lens has a flat field and is telecentric in image (detector) space.

The use of neutral density filter helps in expanding the dynamic range of the instrument. The measurement on color coordinates in various colors spaces is provided by using multiple detectors, each with a characteristic color filter. The incoming spectrum is multiplied by the transmission spectrum of the color filter for each detector. The relative signals on the detectors help in determining the color coordinates. Similarly the CCT can be evaluated.

Reflectometers

Reflectometers measure the reflectance from samples for cases such as reflectance as a function of wavelength, angle of incidence, angle of viewing and polarization. Depending upon the requirements, not all of these parameters are needed. The sample surfaces may be diffuse, specular, or a mix of two. When samples must be characterized by BRDF, scatterometers are used. Reflectometers are discussed in Chap. 35 in this volume and Scatterometers are discussed in Chap. 1 in Vol. V of this *Handbook*.

Goniometers

Goniometers are instruments that measure the irradiance or illuminance distribution of a source or luminaire. They accomplish this by measuring the illumination distribution at a number of points. By locating the detector in the far field with respect to the source or luminaire, one is actually measuring the intensity distribution. The far field is when the irradiance/illuminance distribution closely matches that of the respective intensity distribution, which means the inverse

TABLE 8 Three Types of Standard Goniophotometer with Their Respective Standard Coordinate Systems[74]

	Type A	Type B	Type C
Polar axis	Vertical	Horizontal	Vertical
Vertical angle designation	Y	V	V
Horizontal angle designation	X	H	L
Range of vertical angles*	$Y \in [-90°, 90°]$	$V \in [-180°, 180°]$	$V \in [0°, 180°]$
Range of horizontal angles	$X \in [-180°, 180°]$†	$H \in [-90°, 90°]$*	$L \in [0°, 360°]$‡
Straight ahead/down	Ahead: $Y = 0°, X = 0°$	Ahead: $V = 0°, H = 0°$	Down: $V = 0°, L = 0°$
Primary applications	Optical systems Automotive lighting	Floodlights	Indoor lighting Roadway lighting

*The lower angle is in the nadir direction while the upper angle is in the zenith direction.
†The lower angle is measured to the left from the perspective of the luminaire.
‡Measured from the primary axis of the luminaire.

square law applies. A good rule of thumb is ten times or greater the greatest extent of the emitter. For example, a luminaire with a 100-mm-diameter aperture indicates that measurement should be made at no closer than 1 m. Of course, better results are obtained as the distance between the source and detector is increased. By rotating either the source or detector with respect to the other, the full intensity distribution can be measured. The inclusion of a rotation device on either the luminaire or detector while the other remains fixed defines a goniometer. For the purposes of the lighting community, the luminous intensity is measured, so goniometers are better known as goniophotometers in the community.

There are three standard types of goniophotometers (Type A, Type B, and Type C), which are listed with their design criteria in Table 8. There are also three coordinate systems used for the purposes of the measurement reporting. These spherical coordinate systems are also labeled Types A, B, and C, and they typically conform to the type of goniophotometers.[74] However, individual goniophotometers may be of one type and report measurements in another coordinates system. Table 8 assumes that the goniophotometers types and coordinates systems agree.

For Types A and B goniophotometers the detector is held fixed while the luminaire is located in the rotating device. Typically guidelines or standards define the distance that the detector is located away from the luminaire. For example, for U.S. and European automotive headlamps this distance is 75 ft and 25 m, respectively. Type C goniophotometers have the detector rotate around the horizontal axis of the luminaire while the luminaire is rotated around its vertical axis. This setup is important for sources that have limitations to orientation (e.g., metal halide arc lamps). Figure 33 shows a Type C goniometer that is used to measure the luminance distribution from sources.

There are many other types of goniophotometers, especially those labeled as snapshot systems. Snapshot systems capture an "image" of the intensity distribution through one measurement. Examples include systems with several detectors; rapid scanning systems for smaller sources such as LEDs; camera-capture systems that incorporate an intermediate diffuse, reflective screen; and tapered-fiber bundles integrated to detector arrays.[74]

Surface Measurement Systems

Not only are the illumination distributions, spectra, scatter distributions, and optical characteristics measured, but also the geometry of the optics. These measurareements are done to characterize the geometry of the fabricated optic in regard to the design. This step is done, in conjunction with tests from the previous testing sections, when there is a disagreement between the laboratory and modeling results. There are essentially two methods in use: coordinate measurement method (CMM) and laser scanning. [75,76] CMM uses a probe that is drawn across the surface of the optic, which provides the (x, y, z) data at a series of points on the surface. This method is analogous to using a sphereometer

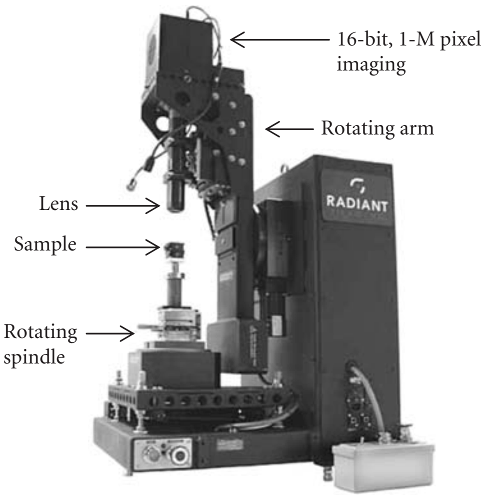


FIGURE 33 Photograph of a source measurement goniometer that is used to ascertain the luminance distribution of the source. The system wobble (electro-mechancial-software runout) is 15 μm to allow for measuring small light sources like LED die. (See also color insert.) (*Courtesy of Radiant Imaging, Inc., model SIG 400.*)

to measure the sag and thus curvature of a lens surface. CMM is a contact method so the optic under test can be detrimentally affected (e.g., scratched) during measurement. Noncontact methods such as laser scanning essentially replace the mechanical probe with a laser beam. The position is measured through location of the reflected spot, triangulation, and/or time of flight as the laser is scanned across the part. Software can then determine the slopes of the test points, and thus rebuild the shape through a point cloud. If the component under test reflects well, then the surface must be coated or a fine, white powder can be placed across the surfaces. Laser scanning is a rapid method to ascertain the part shape. It provides a multitude of points in a short time; however, laser scanning accuracy is currently limited in comparison to CMM.

40.7 LIGHTING APPLICATION AREAS

In this section, we discuss several lighting application areas. We broadly divide the applications into two areas: interior lighting (office, residential, retail and healthcare) and exterior lighting (industrial and transportation). This set of applications is limited; we provide design concepts, metrics and data reference on major application areas. These ideas could be readily applied to other areas of lighting such as entertainment, sports, theatre, and so forth. Each field has its own region-specific and time-dependent guidelines and standards to implement.

The data provided here is primarily from IESNA suggested guidelines, thus exceptions are expected. For example, an office lobby is likely to have far dimmer ambient lighting than dictated by general office lighting guidelines. In essence high-end retail guidelines provide the design goals in order to provide a desired ambience. Although we have provided the guideline data to indicate the relevant specification parameters, by no means is this complete and the guidelines and standards are evolving with time, place, and technology advances. The reader must check the prevalent guidelines for the exact numbers to use. Previous sections of this chapter describe in detail the general aspects of the lighting design process, principles, and techniques for the applications described here. Each of the following subsections provides insights into the specifics of the lighting design process for the given application.

Interior Lighting

Interior lighting includes the office, retail, residential, and health-care facility subfields. In each of these areas there are established guidelines to provide a pleasing environment to the users of the space. Of special importance are required illuminance levels, luminance ratios, and the reduction of glare. The following four subsections describe each of these application areas in more detail.

Office Lighting Modern office lighting has assumed greater importance than in the past as more people work in them. The goals of office lighting include efficient task performance, energy-efficient lighting, nonmonotonic ambient lighting that provides a balance between horizontal and vertical illuminance and minimum glare.

The task surface in offices has historically been the horizontal desk surface. However, computer monitors are ubiquitous these days and present a self luminous vertical task surface. In addition it is specular and reflects light which can cause glare. Lighting goals are to provide adequate task illumination and adequate light in the task vicinity to eliminate eye strain due to varying brightness and disability glare. This is ensured by limiting the maximum luminance ratio of task to nontask regions. Veiling reflections (see section on glare) from computer monitor screens and paper surfaces must be avoided by taking into account source task and eye geometry. The glare from the computer monitor arises typical from ceiling source, and it is avoided by putting a limit upon the maximum ceiling luminance. Glare across the horizontal surface can be eliminated by using low luminance, wide-area lighting from overhead luminaires or special desk lamps (Fig. 24). Daylight from windows at desk level or near the ceiling can be a source of glare and steps such as daylight control via blinds or changing the task-eye geometry with respect to the glare source must be taken into account.

Balancing of daylight with electrical lighting, preferably with automatic controls, is not only energy efficient but also preferred by the workers. Therefore electrical lighting with high CRI (>70) is desirable as it mimics daylight illumination quality better.

Table 9 summarizes the common specifications and major guidelines on office lighting. The reflectivity of room parameters such as walls and ceiling is provided to aid in room modeling to aid in determining the layout of luminaires.

Retail Lighting The goal of lighting for the retail environment is to attract the customer, facilitate evaluation of the merchandise by the ucstomer, and provide light for completing the transaction.[77] There are varying lighting methods dependent on the type of retail store, what goods are being illuminated, and the background. Table 10 provides various guidelines on lighting levels dependent on the type of store and what is being illuminated. Note that this table is not complete by any standard, so the reader is encouraged to consult the literature (see, for example, Ref. 77) for more specific information for a given retail lighting environment. Note that there are particular design issues that have varying importance levels for each type of retail outlet, such as, glare reduction in jewelry and china stores.[78]

The circulation areas are those not typically used for the display of merchandise such as walkways, aisles, and foyers. The general areas are those for the generic display of merchandise. Perimeter areas are the walls where merchandise is placed for sale. Feature areas are where important displays are positioned. Horizontal illuminance values are listed for all of the columns in Table 10 except the perimeter areas, which provide vertical illuminance values. The feature areas have peak illuminance values of 5:1 to 10:1 compare to the respective general area peak illuminance. Of particular note in Table 10, the trends indicate

- Bulk stores, or those described as "big box," tend to have much higher illuminance levels with higher uniformity across areas. This type of illumination provides the user with an abundance of light to fully inspect the merchandise, associated labeling, and compare to similar products.

TABLE 9 Summary of Specifications and Guidelines for Office Lighting

Specifications	Goals
Maximum luminance ratios:	
Task to neighboring areas	3:1 to 1:3
Task to distant regions	10:1 to 1:10
Max ambient illuminance (lx)	500
Max ceiling luminance (nits)	<1000 (in the presence of computer monitors) <425 nits does not cause glare
Reflectivity of room objects* (%)	
Ceiling	≥80
Walls	50–70
Partition	40–70
Furniture	25–45
Floors	20–40
Corridor Floors	>20 (of the illuminance of the adjacent areas)
CRI	>70
Lighting schemes	Direct, indirect and direct-indirect
Key considerations	Eliminate shadows on faces or tasks, glare control, provide a spacious ambience
Ceiling uniformity (max: min)	<8:1 (for indirect lighting only)
Common light sources	Daylighting, LED, CMH, fluorescent, and CFL
Glare sources to be eliminated or reduced	Veiling reflections from direct sources or ceilings on computer monitor screen, reflections from any specular surface including walls and desks

*Valid for matte or diffuse finish.

TABLE 10 Suggested Illuminance Levels for Circulation, General, Perimeter, and Feature Areas for Various Types of Retail Stores[77]

Type of Retail Store	Circulation Area Illuminance (lx)	General Area Illuminance (lx)	Perimeter Area Illuminance (lx)	Feature Area Illuminance (lx)
Warehouse	250–300	750–850	750–850	3750–8500
Supermarket	250–300	750–1000	750–1000	3750–5000
Discount	250–300	750–850	750–850	3750–8500
Mass merchant	200–250	500–600	750–850	2000–5000
Department	200–250	400–500	500–750	2000–3500
Upscale	150–200	300–400	400–800	1500–4000
Specialty	200–250	400–500	500–750	2000–3500
Upscale	150–200	300–400	400–800	1500–4000
Boutique	80–120	200–300	200–600	1000–3000
Jewelry	80–120	200–600	200–600	1000–6000
Upscale China	80–120	200–600	200–600	1000–6000
Drugstore	250–300	750–850	750–850	3750–8500
Home	200–250	400–500	500–750	2000–3500
Furniture	80–120	200–300	200–600	1000–3000

- More specialized or exclusive, the lighting levels tend to be reduced. This type of lighting provides a more intimate environment between the customer and the salesperson with illumination to highlight the item under evaluation.

Essentially, Table 10 can be broken down into three categories: mass merchandising, department, and exclusive stores. At the lower end, mass merchandising, one typically specifies ambient illuminance

TABLE 11 Suggested Illuminance Values for Areas within a Department Store[77]

Department Store Area	Horizontal Illuminance (lx)	Vertical Illuminance (lx)	Very Important Design Issues
Alteration room	500	300	Color appearance and source geometry
Dressing area	300	50	Color appearance and object modeling
Fitting area	500	300	Color appearance and object modeling
Stock room	300	50	
Sales area	300		Direct glare
General merchandise area	500		Color appearance
Feature display	2,500		Appearance of area, color appearance, direct glare, and object modeling
Display window	2,000 (day) 500 (night)		Appearance of area, color appearance, daylighting, object modeling, and reflected glare
Feature	10,000 (day) 5,000 (night)		

between 750 and 1000 lx and a CCT of 3500 to 4100 K. Department stores are in the range of 400 to 600 lx with a color temperature around 3500 K. High-end stores have ambient light levels of 150 to 300 lx and color temperatures of 2700 to 3000 K.

The values provided in Table 10 are guidelines, and values are expected to vary dependent on the background, the items being illuminated, and any external lighting. The reasoning behind this is that observers see luminance rather than illuminance. Thus, the lighting designer must take into account the reflectance, both diffuse and specular, from the merchandise and background. Thus, Table 10 assumes that there is constant reflectance between the features and the background, such that illuminance ratios of 5:1 to 10:1 are specified, when in actuality luminance ratios in this range are prescribed.

Within any type of store there are different lighting levels dependent on the application. Consider, for example, a department store, which is made up of several different environments, from the entrance areas to fitting areas, to general displays areas. Table 11 provides illuminance level guidelines for typical areas in a department store. It also includes the very important design issues for each of the retail areas.

The methods of lighting a given area are dependent on the application of the space. Ambient lighting provides the baseline lighting level, while the addition of secondary lighting units provides the increased illuminance values as listed in Tables 10 and 11. Table 12 provides a synopsis of these other application space lighting demands, including the typical luminaire used and design issues.

As previously noted the lighting designer must remain cognizant of external lighting conditions when specifying the artificial retail lighting environment. A large facet of external lighting is better known as daylighting, and of particular concern are the varying light level that is provided through the day, direct glare through windows and doors, and the strong background to incorrectly situated merchandise. Other aspects of the retail lighting environment include

- The CRI should be 70 or greater for most environments.
- Transitions between spaces in stores should have luminance ratios of no greater than 3:1 for similar neighboring spaces, greater than 3:1 when there is a distinct transition between the neighboring spaces, and 5:1 to 10:1 for abrupt transitions.
- The perimeter area illuminance should be greater than the overhead area in order to draw the attention of the shopper to the merchandise.
- Calculating baseline lighting levels for retail spaces one should use diffuse reflection values of office spaces.

Residential Lighting The goals of residential lighting are to provide ambient illumination to create a pleasing ambience due to a well-lit environment; sufficient task lighting in workspaces such

TABLE 12 Specific Application Space Lighting for Illumination of Merchandise Locations

Application Space Lighting	Typical Luminaires Used	Design Issues
Ambient Light		
Mass merchandising department	Fluorescent and halogen fluorescent, recessed fluorescent and halogen	Uniformity
High end	Recessed fluorescent and halogen, track lighting	Flexibility for change
Perimeter	Fluorescent, incandescent, or HID wall wash, track or recessed spot lighting	Uniform vertical illuminance, hidden luminaires
Rack	Recessed or track dpot lighting	Direct glare reduction
Shelf	Ambient lighting with recessed surface lighting	Direct glare reduction, hidden luminaires
Counter	Focused downlighting	Direct glare reduction, 3 to 5 times ambient lighting
Mirror	Downlighting	Glare reduction, color appearance, object modeling, and consistent lighting with use of product
Showcase	Fluorescent and fiber-optic lighting	Hidden luminaires
Accent	Small (point-like) sources	Provide luminance ratios of 5:1 to 15:1
Decorative	Sconces, chandelier, table, and torchiere lamps	For high-end stores to provide a desired look and feel

as office, garage, kitchen, and workshop; and decorative lighting and accent lighting for lit object displays. A variety of lighting techniques are used to create layers of lighting that perform different lighting functions (see book by Whitehead on “Residential Lighting” in Ref. 26). Like retail lighting, residential lighting can be quite complex and creative. Although we summarize many common guidelines for residential lighting requirements in Table 13, other specialized guidelines are more relevant in some areas of the house, such as retail lighting guidelines for the kitchen, office lighting guidelines for the home office, industrial lighting guidelines for task lighting in garage or workshop and exterior lighting guidelines for landscaping and the house facade. Thus depending upon the purpose of a specific region of the house the lighting scheme must be tailored. However, the different lighting schemes used across the house must be gently blended into one another. For example, exterior lighting for residences includes the lighting of entry, walkways, and landscape. Although the primary goals are to provide direction, safety, identification and aesthetic appearance, achieving a balance between interior and exterior lighting makes the interior and exterior spaces extensions of one another. Residential lighting should be customized to maximize the comfort of the inhabitants especially when the inhabitants are disabled or elderly. For example, elderly people require much higher levels of illumination especially for task performance.

Other than those areas that require excellent task lighting such as offices or workshops, the limits on luminance ratios are relatively relaxed when compared to other lighting applications, such as the maximum residential luminance ratio of 5:1 between Task and neighboring areas is higher than that of office lighting of 3:1. The idea of limiting the maximum luminance ratio is to minimize visual discomfort caused by disability glare and adapting to variations in brightness. The integration of daylight with artificial lighting is highly desirable.

Health-Care Facility Lighting The lighting in health-care facilities, which includes hospitals, outpatient clinics, chronic and extended care centers, and other facilities, requires careful understanding of the lighting requirements for not only the patients but also the individuals working therein. The lighting must be pleasing and comforting to the patients in order to put them at ease and assist in their healing. The patients and visitors have a wide range of ages, with the majority being elderly;

TABLE 13 Summary of Specifications and Guidelines for Residential Lighting

Specifications	Goals
Maximum luminance ratios	
Task to neighboring areas	5:1 to 1:5 (in general) 3:1 for demanding tasks such as sewing
Task to distant regions	10:1 to 1:10
Lumnaire to ceiling	20:1
Hallway or stair to adjacent area	1:5
Reflectivity of room objects* (%)	
Ceiling	60–90
Walls, curtains, draperies†	35–60
Floors†	40–70
Average luminance for luminaire (nits)	1700
Maximum luminance for luminaire (nits)	2700 (in utility areas)
CRI	>80 (kitchen and clothing closets)
Lighting schemes	Direct, indirect, and direct-indirect
Key considerations	Eliminate shadows on faces or tasks, glare control, providing a spacious and cozy ambience as well cozy as desired
Common light sources	Daylighting, LED, fluorescent, and CFL.
Glare sources to be eliminated or reduced	Direct glare from light sources, veiling reflections, indirect glare from shiny objects

*Valid for matte or diffuse finish.
†Reflectance of walls and floor can be increased by 40% and 25%, respectively, to improve visual task lighting where needed.

therefore, there is a large variance in the response to lighting, especially increased glare sensitivity, loss of contrast sensitivity, the need for higher lighting levels, and slow adaptation to changes in brightness as one ages.[79] The lighting levels also need to provide for the medical staff such that they can effectively carry out their job—from meticulous and demanding surgery to patient interviews and diagnoses to manning the check-in desk. Finally, since in a number of these facilities patients may be there for extended periods, circadian system illumination levels that conform to the human biological clock are the norm. As can be seen, there is an extensive range of tasks, observers, and daily requirements for illumination in health-care facilities, thus, making the lighting design a challenging assignment.

Foremost is the need to specify the light requirements for a given location based on the tasks to be performed there. Table 14 provides a synopsis of the illuminance level guidelines and important design issues for a number of locations in health-care facilities; however, since these are only guidelines, controls for the area illumination are often available to the medical staff and/or patients. This flexibility in the control of lighting levels based on the specific function of the environment and even mood of the occupants is important in health-care facilities. Note that there are many other areas and functions than can be included in Table 14, so the reader is encouraged to see Ref. 79 for this additional information.

The operating room environment is especially challenging since the lighting is preferentially directed to the task area; however, this has the potential of creating large luminance ratio variation within the room. Practices suggest three regions within the operating room with the following luminance ratios: task area to the surgical table of 3:1 or less and task area to the background (i.e., walls) of 10:1 or less. Additionally, there are specific guidelines for the finishes for the surfaces within the surgery theatre as provided in Table 15. In most cases all surfaces are white or pastels with a matte finish to reduce reflected glare. The lighting in an operating room is provided by a multitude of sources including ambient and even daylighting, directed spotlights, surgeon headlamps, and increasingly fiber-optic lighting.

Concurrent to the design guidelines of Table 14, the lighting designer must remain cognizant of the specifications for reflectances of the walls, floor, ceiling, and other objects that occupy the design area.

TABLE 14 Suggested Illuminance Values and Other Criteria in Health-Care Facilities[79]

Health Care Facility Area and Current Function	Horizontal Illuminance (lx)	Vertical Illuminance (lx)	Important Design Issues
Patient room			
Normal	200+, as home	30+, as home	Patient control, CRI >80, daylighting
Examination	1000	300	Glare reduction, CRI >80, CCT>3000 K, doctor control
Observation (night)	30	30	Red/amber CCT, no higher than 18” off floor
Nursing station	300	50	Glare reduction, CRI>80
Critical care unit			
Normal	300	50	Patient control, CRI>85, daylighting
Examination	1000	300	Glare reduction, CRI>85, CCT>3000 K, doctor control
Nursery	100	30	Glare reduction, CRI>80, lighting control, daylighting
Mental health center	As per other functions	As per other functions	Daylighting, CRI >80, CCT of 4100–5000 K with fluorescent, 3500 K otherwise, glare reduction
Operating room			
Normal	1000	500	CRI >85, matched light
Table	25000+ in 20-cm spot (adjustable)	1000	Sources for illumination, shadow, and glare reduction, doctor control, CCT of 3500–6700 K, high uniformity
Dental unit			
Normal	300	50	
Examination	24000+ in central spot	500	As operating room
Radiography unit	50, but depends on test	30, but depends on test	CRI >80, glare reduction, doctor control
Pharmacy	300	100	Glare reduction, high uniformity, CRI >80

TABLE 15 Suggested Reflectances for the Various Objects in a Health-Care Facility Room for a General Application and the Operating Room Environ[79]

Surface	General Reflectance	Operating Room Reflectance
Ceiling	70–80%	90–100%
Walls	40–60%	60%
Furniture/fabrics	25–45%	0–30%
Equipment	25–45%	25–45%
Floors	20–40%	20–30%

Table 15 provides this data for two locations, general and operating room. Using these values in conjunction with the optical design process one can find suitable illumination configurations to provide the Table 14 guidelines.

Industrial Lighting The goals of trial lighting are to provide energy efficient lighting with adequate task and ambient lighting, direction, safety, and visual comfort. Many common requirements for industrial lighting requirements are summarized in Table 16.

TABLE 16 Summary of Commonly Suggested Specifications and Guidelines for Industrial Lighting

Specifications	Goals
Maximum luminance ratios	
Task to neighboring areas	3:1 to 1:3 (in general)
Task to distant regions	10:1 to 1:10
Luminaire (including daylight sources) to adjacent surfaces	20:1
Anywhere within the FOV	40:1
Reflectivity of objects* (%)	
Ceiling	80–90
Walls	40–60
Floors	≥20
Desk/bench tops, machines, equipment	25–45
CRI	>65
Lighting schemes	Direct, indirect, and direct-indirect
Key considerations	Eliminate shadows on faces or tasks, provide high illuminance uniformity, sufficient illuminance, and glare control
Common light sources	Daylighting, LED, fluorescent, HID, and CFL
Glare sources to be eliminated or reduced	Direct glare from light sources, veiling glare, indirect glare from shiny objects
Direct view of the luminaire (deg)	>25 (preferably >45)

*Valid for matte or diffuse finish.

The ambient lighting is provided by daylighting and/or large area, overhead, wide angle luminaires (direct and semidirect). Task lighting is provided by fixed and portable direct or diffuse light sources. Backlights are used for translucent task surfaces. Direction of illumination with respect to the view angle(s) is important in tasks where surface features of the object cause shadows to enhance depth perception. Illumination at grazing incidence is used to highlight specific feature that can scatter light and render themselves visible. To emphasize specular but uneven surfaces, specific patterns of light (like bright and dark lines) can be projected onto the task surface to be reflected into the viewer's eyes. For lighting in regions where there is a high density of workstations or areas where there are several similar process, a high level of uniformity in horizontal illuminance is recommended. In such areas, variation of horizontal illuminance should be less than 1/6th the average horizontal illuminance. Otherwise, the variations in luminance across the work space must be within the luminance ratios prescribed in Table 16. The level of horizontal illuminance needed varies with task. In industrial lighting, the quality of horizontal illuminance is of special importance as efficient and safe task performance is needed. The reader is referred to IESNA published guidelines for horizontal illuminance values for a wide variety of tasks in different industries.[80]

In addition to providing the task lighting and ambient lighting, it is often necessary to provide additional lighting dedicated for emergency, safety, and security within the industrial complex and its exteriors.

Visual discomfort must be avoided especially during task performance and in situation where safety could be compromised. Special attention should be given to situations causing veiling reflections and glare. The various limits placed on the luminance ratios in Table 16 between task and nontask regions help eliminate the impact of glare.

Exterior Lighting

Of course the primary aspect of exterior lighting is to provide illumination during hours of darkness. The lighting not only provides illumination for general use, it also provides safety and security; indication of direction of travel for paths, roadways, and so forth; and architectural enhancement.

External lighting is attempting to replicate the illumination of the sun; however, it can in no fashion accomplish this feat. The illumination provided by any lighting source cannot match that of the sun, which means that the sky will appear dark rather than blue; numerous sources are required to provide the necessary illumination level so glare from the many sources is a major factor; distance from the light sources, mesopic vision and even scotopic levels may be demanded; and the many sources can confuse the viewer such that objects can be difficult to discern from one another.[81] Additionally, this section is rather broad in scope, including design aspects such as roadway lighting, path lighting, outdoor event lighting, and façade illumination. Thus, the reader may need to consult specific literature for a certain type of lighting. Please consult the transportation lighting section for further information on vehicular and roadway. In the next two subsections details are presented about the issues present for external lighting design and design examples, excluding the transportation applications discussed later.

External Lighting Design Issues There are several topics that a lighting designer for external spaces must consider. First and foremost is the specific application guidelines (for example, see the section on illuminating roadways), glare issues, light pollution and trespass, and perception issues. All of these factors are interrelated, and the subsections herein provide insight into them.

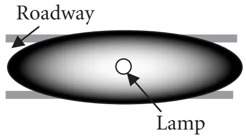
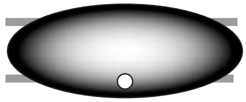
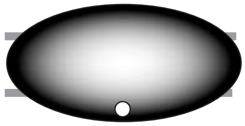
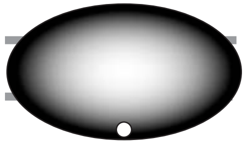
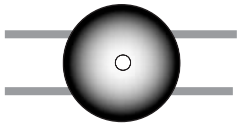
Glare A primary issue of external lighting is glare. Since users of a space in the hours of darkness are relying on nonphotopic vision, glare can blind the viewer as one approaches a bright source thus not only causing the scotopic vision receptors (e.g., rods) to naturally saturate but also the photopic vision receptors (e.g., cones). This "blinding" is due to disability glare, which will hide objects or reduce their contrast. Other levels of glare can also inhibit observation: discomfort glare, which is attributed to a large variance on and around the object under view; and annoyance glare, which is light that in the opinion of the observer should not be present, such as light trespass.

The major source of glare is directly from the source in comparison to the object under observation. Comparison between the luminaire luminance to the object's illuminance is the factor that often defines the level of glare, from disabling to discomfort. Depending on the orientation of the object one either compares the horizontal or vertical surface luminance to the luminaire luminance. The horizontal luminance is used for horizontal surfaces such as walkways and roads, while the vertical luminance is used for vertical surfaces such as building façades, people, and structures.

Light Pollution and Light Trespass Associated to glare is light pollution and light trespass. Light pollution, also called sky glow, is light that is directed upward to the atmosphere.[82] This sky glow hides stars from observation, and on cloudy days provides a glow, typically red in hue, which can distract from one's appreciation of the view of their surroundings. Astronomers have been particularly vocal in the reduction of light pollution, and there is increasingly consideration of energy efficiency demands. In 2008 it was hypothesized that over $10B U.S. was wasted through light pollution,[83] which means that this amount has only increased since then. Like light pollution, light trespass is unwanted light, but in this case it is light that illuminates objects outside of the intended illumination region.[84] Such stray light enters through windows, illuminates someone's property, or can impair the vision of drivers. Light pollution and trespass arise from improperly designed luminaires. There are increasing regulations for the design of outdoor lighting to alleviate such concerns. A primary correcting factor is the use of luminaire cutoffs as presented in the section on luminaire design.

External Lighting Example Pole lighting is the most common form of outdoor illumination providing a significant amount of light, safety and security, and indication of the path of travel for walkways, roadways, and so forth. In the United States, there are five primary forms of classifications of pole-mounted luminaires, but there are numerous variations based upon the lighting requirements, the shape of the illumination region, and illumination level demands.[85] Table 17 provides descriptions of the five types, the typical application(s) of the type, and an iso-illuminance plot for each of the types. Per the iso-illuminance plots of Table 17, the larger the illumination distribution the more ground is illuminated, which means not only the roadway is illuminated but also sidewalks, shoulders, and other neighboring areas. Thus, Type IV and V luminaires tend to have more light trespass.

TABLE 17 Description, Applications, and Iso-Illuminance Plots for the Five Primary Luminaire Types Used for Pole-Mounted Outdoor Lighting[85]

Type	Description	Applications	Iso-Illuminance Plot
I	Little setback to the road or mounted over the roadway; narrow oval illumination distribution	Roadways	
II	Moderate setback to pedestrian area; moderate oval illumination distribution	Pedestrian areas	
III	Large setback to the road; Moderate elliptical illumination distribution	Pedestrian areas roadways, parking lots	
IV	Great setback to the roadway; large elliptical illumination distribution	Roadways	
V	Mounted over pedestrian area rotationally symmetric illumination	Pedestrian areas parking lots	

Transportation Lighting

Transportation lighting includes the subfields of vehicular and roadway lighting. In both cases rather than just guidelines, there are many stringent governmental standards that must be met by the illumination systems. For example, there are governmental standards for traffic lights and vehicular taillights and headlights. If these standards are not met, then the lighting systems are not legal for use on our roadways.

Vehicular Lighting Vehicular lighting is the external illumination aspects of vehicles, including automobiles, motorcycles, snowmobiles, emergency vehicles, airplanes, ships, and heavy machinery including construction, industrial and agricultural. Ground vehicles are especially important due to their pervasiveness in society. For the remainder of this section, we highlight ground vehicle standards, but there are similar standards for other types of vehicles. In the United States, the U.S. Federal Government standardizes the lighting requirements through the Federal Motor Vehicle Safety Standards (FMVSS) from the offices of the National Highway Traffic Safety Administration (NHTSA) within the Department of Transportation (DOT). In Europe and a number of other countries spanning the globe, the United Nations Economic Commission for Europe (UNECE or better known as ECE) sets the standards. The FMVSS calls upon the standards delineated by the Society of Automotive Engineers (SAE) to provide the explicit lighting requirements for distinct lighting systems. While FMVSS 108 provides the framework for lighting systems on ground vehicles within the United States,[86] the SAE provides the accepted standards to design into the lighting systems.

For example, SAE standard J581 provides the upper-beam requirements to be an accepted high beam on U.S. roads,[87] while R113 is the accepted ECE standard.[88] The associated low-beam standards are SAE J582 in the U.S.[89] and ECE R112 in Europe,[90] but there is currently an active dialogue to harmonize the standards between the U.S., European, and Japanese markets. The SAE J1735 standard is currently addressing the low-beam harmonization, and in time it will also address the high-beam requirements. The end results will be, excepting the inherent difference of left-hand (e.g., United Kingdom) and right-hand (e.g., United States) traffic, harmonization has the goal of making the lighting standards the same at as many places possible across the globe. This increased standardization means that the design and fabrication costs will be reduced for manufacturers.

There are essentially two types of lighting on a ground vehicle: forward lighting for illuminating the road surface and nearby surrounds and indicator and warning lighting including turn signals, brake lights, side markers, and tail lights. Each vehicular light system is defined by its own set of regulations including the distribution of light, the color and characteristics of the protective lens, mounting requirements, and a number of enviromechanical tests including vibration, dust, moisture, corrosion, and warpage. In the United States, the test procedures and protocols are typically governed by SAE J575, while each individual standard provides the photometric requirements. In the United States, the photometric requirements are the luminous intensity distribution at a distance of 18.3 m from the lamp, while the ECE requirements are for the illuminance distribution at a distance of 25 m. The typical instrument to make this measurement is a goniometer that holds the lamp and allows it to be rotated so that a different angle is incident on a fixed photodetector at the end of an absorbing light tunnel. By rotating the lamp within the goniometer and making a series of measurements the full distribution of light can be determined; however, rather than measuring across the whole lit region, the standards dictate a series of test points and test areas that must be measured. In the remainder of this section, we highlight two applications: low-beam headlamp and stop lamp. In each subsection, the requirements for both U.S. and ECE standards are provided, a depiction of a typical distribution of light, discussion of design strategies, and additional optical requirements of the standards. Note that while we highlight these two applications and their respective standards, there are numerous other optical standards governing the external lighting systems on vehicles (see Refs. 86 to 92) for further information about these additional standards).

Design and Standards for a Low-Beam Headlamp A headlamp, as shown in Fig. 34*a*, must illuminate the road surface for the driver, illuminate to the sides for both the driver and any other observer, provide a low level of illumination to oncoming drivers, and in all cases remove the formation of hot spots above the horizon such that glare is not a concern to oncoming traffic. Of note in Fig. 34*a* is

- High-beam luminaire:
  - Rightmost recess of the lamp.
  - Faceted reflector, but other options include smooth, tailored reflector (e.g., NURBS surface as designed in CAD); faceted lens in conjunction with smooth reflector (e.g., parabolic); and projection lens in conjunction with reflector.

(a) (b)

FIGURE 34 (*a*) A faceted headlamp including high-beam (right), low-beam (middle), and turn signal (left) luminaire. Note the yellowish tinge of the turn signal, which is due to the coating placed on the bulb used therein. (*b*) A faceted taillight including the following functions: tail (upper left), stop (upper right), turn signal (lower right), reflex reflector (lower middle), and backup (lower left). (See also color insert.)

- Filament source, but other options include high-intensity discharge lamp or array of white-light LEDs.
- Low-beam luminaire:
  - Middle recess of the lamp.
  - Faceted reflector, but other options are as the high-beam luminaire above.
  - Filament source, but other options are as the high-beam luminaire above.
  - Bulb shield: reflective structure in the middle of the lamp and covers direct view of the filament source. The bulb shield greatly alleviates direct light above the horizon.
- Turn signal luminaire:
  - Leftmost recess of the lamp.
  - Faceted reflector, but other options are as the high-beam luminaire above.
  - Filament source, but other options are as the high-beam luminaire above. Note that the bulb has a yellow coating placed on its glass envelope, which then provides the yellowish appearance of such lamps. This coating provides the color as specified by its respective standard.

Headlamp reflectors have a parabolic base shape in order to provide a high degree of collimation in the forward direction. The reflector, both faceted and smooth, is then deformed to provide the distribution that meets standards. Designing such deformations can be difficult, but there are software codes to assist in the process. Design guidelines include a goal of having the emitted radiation only incident once on the reflector; avoid secondary interactions with the bulb shield, bulb, or reflector shelves (i.e., the reflector sides, as shown in Fig. 34*a*); and angling intersegment fillers (i.e., spaces between the facets) such that they cannot be directly seen from the source emission region. In order to avoid secondary interactions with the bulb and its respective shield, one typically angles the reflected light across the luminaire, except that striking near the reflector near the source. The latter is directed away from the source. In systems with projection and faceted lenses, the reflector is there to capture bulb emission, while the lens provides the required distribution that meets standards. Due to demanding illumination requirements, it is best if most of the bulb emission is incident on the reflector; therefore, in almost all cases the filament or arc is oriented along the axis of the reflector (i.e., orthogonal to the filament as shown in Fig. 13). This axial filament orientation also ensures less light goes above the horizon in the low-beam luminaire.

Table 18 provides the SAE J582 luminous intensity requirements, while Table 19 provides the ECE R1 12 requirements. Figure 35 shows a typical SAE luminous intensity distribution that meets the requirements of Table 18. Figure 36 shows a typical ECE illuminance distribution that meets the requirements of Table 19. The SAE standards of Table 18 and Fig. 35 are in the units of candelas

TABLE 18 SAE J582 Standard Photometric Requirements for Auxiliary Low-Beam Lamps[89]

Test Point (Deg, ±0.25°)	Max Luminous Intensity (cd)	Min Luminous Intensity (cd)
10U to 90U	75	—
1.5U–1L to L	300	—
1.5U–1R to R	300	—
0.5U–1L to L	400	—
0.5U to 1R to 3R	400	—
0.5D–1R to 3R	25,000	2,000
0.5D–1L to L	10,000	—
5D–4R	—	3,000
5D–4L	—	3,000
1D–1R	—	10,000
3D–3R	5,000	—
4D–V	3,000	—
2.5D–15L	—	1,500
2.5D–15R	—	1,500

TABLE 19 ECE R112 Standard Photometric Requirements for Class A Passing (i.e., Low-Beam) Lamp for Right-Hand Traffic[90]

Test Point Label	Horizontal Location (mm)	Vertical Location (mm)	Max. Illuminance (lx)	Min. Illuminance (lx)
B50L	1500L	250U	0.4	—
75R	500R	250D	—	6
75L	1500L	250D	12	—
50L	1500L	375D	15	—
50R	750R	375D	—	6
50V	V	375D	—	—
25L	3960L	750D	—	1.5
25R	3960R	750D	—	1.5
Zone III	See Fig. 36	See Fig. 36	0.7	—
Zone IV	2250L to 2250R	375D to 750D	—	2
Zone I	L to R	750D to D	20	—

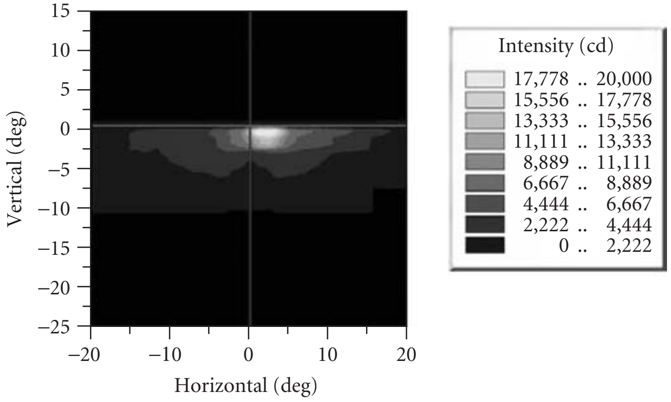


FIGURE 35 Luminous intensity (cd) distribution for the SAE low-beam requirements of Table 18. (See also color insert.)

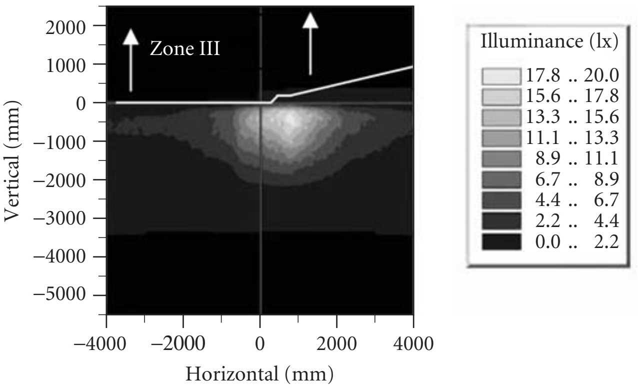


FIGURE 36 Illuminance (lx) distribution for the ECE passing/low-beam requirements of Table 19. (See also color insert.)

(cd, lumens/steradian). The test points are given in degrees and a letter designation, which mean U = up direction, D = down direction, L = left direction, and R = right direction as measured from the point (H, V), which is the center point where H = horizontal and defines the horizon, and V = vertical and defines the lane of traffic. The ECE standards of Table 19 and Fig. 36 are in the units of lux (lx, lumens/m^2), and, while the letter designations still hold, the test point locations and zones are given as position coordinates in millimeters (mm).

Design and Standards for a Stop Lamp A taillight, as shown in Fig. 34*b*, is typically comprised of a number of different functions, such as a stop light, turn signal, backup lamp, and so forth. The taillight of Fig. 34*b* has the following optics in its functions.

- Tail lamp (upper left, red): for night-driving conditions or when headlamps are on. Indicates to follwing traffic the presence of the vehicle during reduced lighting conditions. The governmental standards are SAE J585 and ECE. R7
- Stop lamp (upper right, red): indicates when the driver has applied the brakes. This luminaire is also lit for night driving conditions but a lower output level. The governmental standards are SAE J586 and ECE R7.
- Turn Signal Lamp(lower right, red): indicates the driver is to make a turn a turn in the designated direction. The governmental standards are SAE J588 and ECE R6.
- Reflex reflectors (middle right, red): this area, directly neighboring the turn signal is comprised of prism structures that provide retroreflection to the driver of following vehicles. It is important for dark-driving conditions to highlight the presence of this vehicle to following drivers or indicate its presence when the vehicle is not in operation. Note that this function of the taillight is passive in the sense that no internal light source is used. The governmental standards are SAE J594 and ECER3.
- Backup lamp (lower left, white): this luminaire indicates when the vehicle is in reverse. The governmental standards are SAE J593 and ECE R6.

In Fig. 34*b*, faceted reflectors are used for all the active luminaires. Typically, a transverse filament is used, as per Fig. 13, since the illumination standards for taillight functions are quite broad angularly. Thus, direct radiation from the filament is useful to filling in the required light distribution, while the reflected component of the illumination fills in the required hot spots. LEDs are replacing filament lamps to become the norm for most taillight functions. For LED sources, refractive optics that also employ total internal reflection provide a better means to meet the illumination requirements.

In the remainder of this section, we focus our attention on the design and standards of the stop lamp function, but the other taillight functions have similar requirements. The stop lamp is to inform following vehicles and pedestrians that the vehicle is slowing. In Fig. 34*b*, the stop lamp is located on the upper right of the taillight. Table 20 provides the SAE J586 luminous intensity requirements,[91] while Table 21 provides the ECE R7.[92]

Figure 37 shows a typical SAE luminous intensity distribution that meets the requirements of Table 20. Figure 38 shows a typical ECE illuminance distribution that meets the requirements of Table 21. The SAE standards of Table 20 and Fig. 37 are in the units of candelas (cd, lumens/steradian). The ECE standards of Table 21 and Fig. 38 are in the units of candelas (cd, lumens/steradian). In all cases, the letter designations as per the previous section (headlamps), but in this case the angles are with respect to rear direction of the vehicle.

Roadway Lighting There are multiple subfields that make up roadway lighting: street lighting, roadway signage, tunnel lighting, and integration of collocated pedestrian, bike, and analogous areas. The goal of all forms of roadway lighting is to reduce the potential of accidents, aid in the flow of traffic, provide a higher level of safety and security, and assist in commerce during hours of darkness. There are a multitude of light sources that affect roadway lighting, including the external lighting from vehicles (see section on vehicular lighting); direct roadway lighting, which is the subject of this section; traffic lights, as governed in the United States by the International Transportation Engineers

TABLE 20 SAE J586 Standard Photometric Requirements for a Stop Lamp*

Zone	Test Point (Deg.)	1 Lit Section Min. Luminous Intensity (cd)	2 Lit Sections Min. Luminous Intensity (cd)	3 Lit Sections Min. Luminous Intensity (cd)
I	10U–5L	9.6	11.4	13.2
	5U–20L	6	7.2	9
	5D–20L	6	7.2	9
	10D–5L	9.6	11.4	13.2
	Zone Total	52	62	74
II	5U–V	18	21	24
	H–10L	24	28.2	33
	5D–V	18	21	24
	Zone Total	100	117	135
III	5U–V	42	49.2	57
	H–5L	48	57	66
	H–V	48	57	66
	H–5R	48	57	66
	5D–V	42	49.2	57
	Zone Total	380	449	520
IV	5U–V	18	21	13.2
	H–10R	24	28.2	9
	5D–V	18	21	9
	Zone Total	100	117	13.2
V	10U–5R	9.6	11.4	74
	5U–20R	6	7.2	24
	5D–20R	6	7.2	33
	10D–5R	9.6	11.4	24
	Zone Total	52	62	135
Maximum	Any point above	300	360	420

*The stop lamp is comprised of up to three distinct lit sections over the extent of the taillight for the stop lamp function. Each zone has a number of test point minima that must be realized and the summed total of all test points within a zone. The last line of the table indicates the maximum luminous intensity that can be measured at any test point.[91]

TABLE 21 ECE R7 Minimum and Maximum Photometric Requirements for a Stop Lamp*

Test Point (Deg.)	1 Lamp Illumination Level: Min. Luminous Intensity (cd)	1 Lamp Illumination Level: Max. Luminous Intensity (cd)	2 Lamp Illumination Levels: Min. Luminous Intensity (cd)	2 Lamp Illumination Levels: Max. Luminous Intensity (cd)
10U–5L	12	37	6	16
10U–5R	12	37	6	16
5U–20L	6	18.5	3	8
5U–10L	12	37	6	16
5U–H	42	129.5	21	56
5U–10R	12	37	6	16
5U–20R	6	18.5	3	8
V–10L	21	64.75	10.5	28
V–5L	54	166.5	27	72
V–H	60	185	30	80
V–5R	54	166.5	27	72
V–10R	21	64.75	10.5	28
5D–20L	6	18.5	3	8
5D–10L	12	37	6	16
5D–H	42	129.5	21	56
5D–10R	12	37	6	16
5D–20R	6	18.5	3	8
10D–5L	12	37	6	16
10D–5R	12	37	6	16

*The two categories are for a lamp that is either lit or not lit (e.g., 1 lamp illumination level) and for a lamp that has an unlit, partially lit, and fully lit state (e.g., 2 lamp illumination levels.[92]

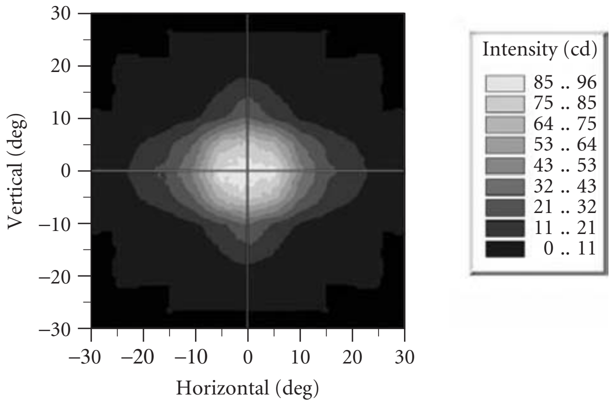


FIGURE 37 Luminous intensity (cd) distribution for the SAE stop lamp requirements of Table 20 (1 lit section). (See also color insert.)

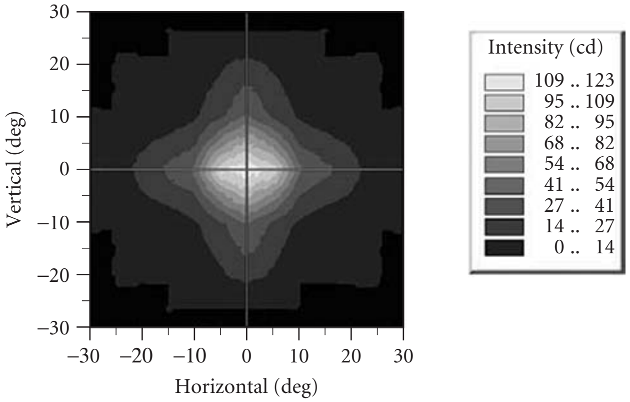


FIGURE 38 Luminous intensity (cd) distribution for the R7 stop lamp requirements of Table 21 (1 lamp illumination level). (See also color insert.)

society; and lighting from other sources such as residential, industrial, and retail. An added difficulty of roadway lighting is the harsh conditions in which they reside. There are stringent maintenance demands that include replacement of sources, cleaning of the optics, and trimming of foliage around the luminaire.[93]

Street Lighting There are essentially three metrics for defining the lighting of a roadway: illuminance (lux, lumens/m^2), luminance (nit, lumens/sr/m^2), and small target visibility (STV).[94] Illuminance modeling provides the level of illumination across a surface. Luminance modeling predicts the level of light (i.e., glare), both direct and reflected, that is directed to a driver. STV is the visibility of a target array (18 × 18 cm^2 and 50 percent reflective) on the road. Table 22 provides the illuminance, luminance, and STV guidelines for a number of road types, four road surfaces in dry conditions, and the interaction level with pedestrians. The illuminance and luminance ratios of Table 22 provide limits such that disabling glare does not blind drivers or pedestrians. Table 23 qualifies the road types, the four road surfaces, and the pedestrian interaction levels of Table 22.

TABLE 22 Illuminance, Luminance, and STV Guidelines for the Type of Road, the Road Surface Classification, and the Interaction Level with Pedestrians[94]

Road	Ped. Level	Road Surface R1 (lx)	Road Surface R2/R3 (lx)	Road Surface R4 (lx)	Illum. Uni. Ratio E_{avg}/E_{min}	Avg. Lum. L_{avg} (cd/m^2)	Avg. Lum. Uni. Ratio L_{avg}/L_{min}	Max. Lum. Uni. Ratio L_{max}/L_{min}	Veiling Lum. Ratio L_{Vmax}/L_{avg}	STV Weight Avg. VL	STV Avg. Lum. L_{avg}(cd/m^2) <7.3 m	STV Avg. Lum. L_{avg}(cd/m^2) ≥7.3 m	STV Lum. Uni. Ratio L_{max}/L_{min}
Class A Freeway	NA	6	9	8	3	0.6	3.5	6	0.3	3.2	0.5	0.4	6
Class B Freeway	NA	4	6	5	3	0.4	3.5	6	0.3	2.6	0.4	0.3	6
Expressway	High	10	14	13	3	1	3	5	0.3	3.8	0.5	0.4	6
	Medium	8	12	10	3	0.8	3	5	0.3	3.8	0.5	0.4	6
	Low	6	9	8	3	0.6	3.5	6	0.3	3.8	0.5	0.4	6
Major	High	12	17	15	3	1.2	3	5	0.3	4.9	1	0.8	6
	Medium	9	13	11	3	0.9	3	5	0.3	4	0.8	0.7	6
	Low	6	9	8	3	0.6	3.5	6	0.3	3.2	0.6	0.6	6
Collector	High	8	12	10	4	0.8	3	5	0.4	3.8	0.6	0.5	6
	Medium	6	9	8	4	0.6	3.5	6	0.4	3.2	0.5	0.4	6
	Low	4	6	5	4	0.4	4	8	0.4	2.7	0.4	0.4	6
Local	High	6	9	8	6	0.6	6	10	0.4	2.7	0.5	0.4	10
	Medium	5	7	6	6	0.5	6	10	0.4	2.2	0.4	0.3	10
	Low	3	4	4	6	0.3	6	10	0.4	1.6	0.3	0.3	10

TABLE 23 Road Types and Surfaces, and Pedestrian Interaction Levels as per Table 22[94]

Road Type	
Class A Freeway	Divided high traffic highways with full access control
Class B Freeway	All other divided highways with full access control
Expressway	Divided highways with limited access control
Major	Primary roadways within and leaving metropolitan areas
Collector	Service roads connecting major and local roadways
Local	Provide direct access to residential, retail, and industrial areas
Road Surface Class	
R1	Portland cement concrete and asphalt with at least 12% artificial brightener aggregates; treat as diffuse
R2	Asphalt road surface with a minimum 60% gravel aggregate; treat as both diffuse and specular
R3	Asphalt with dark aggregates; slightly specular
R4	Smooth asphalt surface; specular
Pedestrian Interaction	
High	Large amount of pedestrian traffic during hours of darkness (100 or more pedestrians in one block during an hour): retail and entertainment areas
Medium	Moderate amount of pedestrian traffic during hours of darkness (11 to 100 pedestrians in one block during an hour): office area, apartment area, older city neighborhoods
Low	Little pedestrian traffic during hours of darkness (10 or less pedestrians in one block during an hour): rural and suburban areas

The luminaire cutoff classification, as described earlier, is used extensively in the design of roadway lighting. The luminaire cutoffs suppress glare to drivers and pedestrians while also alleviating light pollution and light trespass.

There are a number of other road types (e.g., sidewalks, bike paths, and intersections), environmental conditions (e.g., fog, rain, and wet roads), and special considerations with interaction with pedestrians. The reader is encouraged to consult Ref. 94 for these additional circumstances.

Sign Lighting A number of governmental standards have been developed for the lighting of road signs, but a set of guidelines have been developed by the IESNA.[95] Light for signs can be from external sources (e.g., car headlamps) or an internal source for a transmissive sign. Externally lit signs either make use of associated lights that illuminate it or retroreflectors that reflect back to the observer. In the United States the Federal Government provides the standards that must be met for lit roadway signage.[96]

Tunnel Lighting Tunnel lighting is an important factor to increase drive safety while also allowing drivers to maintain their speed. In the United States a structure is considered a tunnel when it is greater than 25 m in length.[97] Distances greater than this require additional lighting to supplement any available daylight. Tunnel lighting is broken up into a number of regions including the approach, adaptation, threshold, transition, interior, and exit zones. Each of these zones has different guidelines to ensure driver comfort; however, these guidelines are dependent on the time of the year, the average speed of traffic, and the presence of oncoming traffic in undivided tunnels. For more information please consult Ref. 97.

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