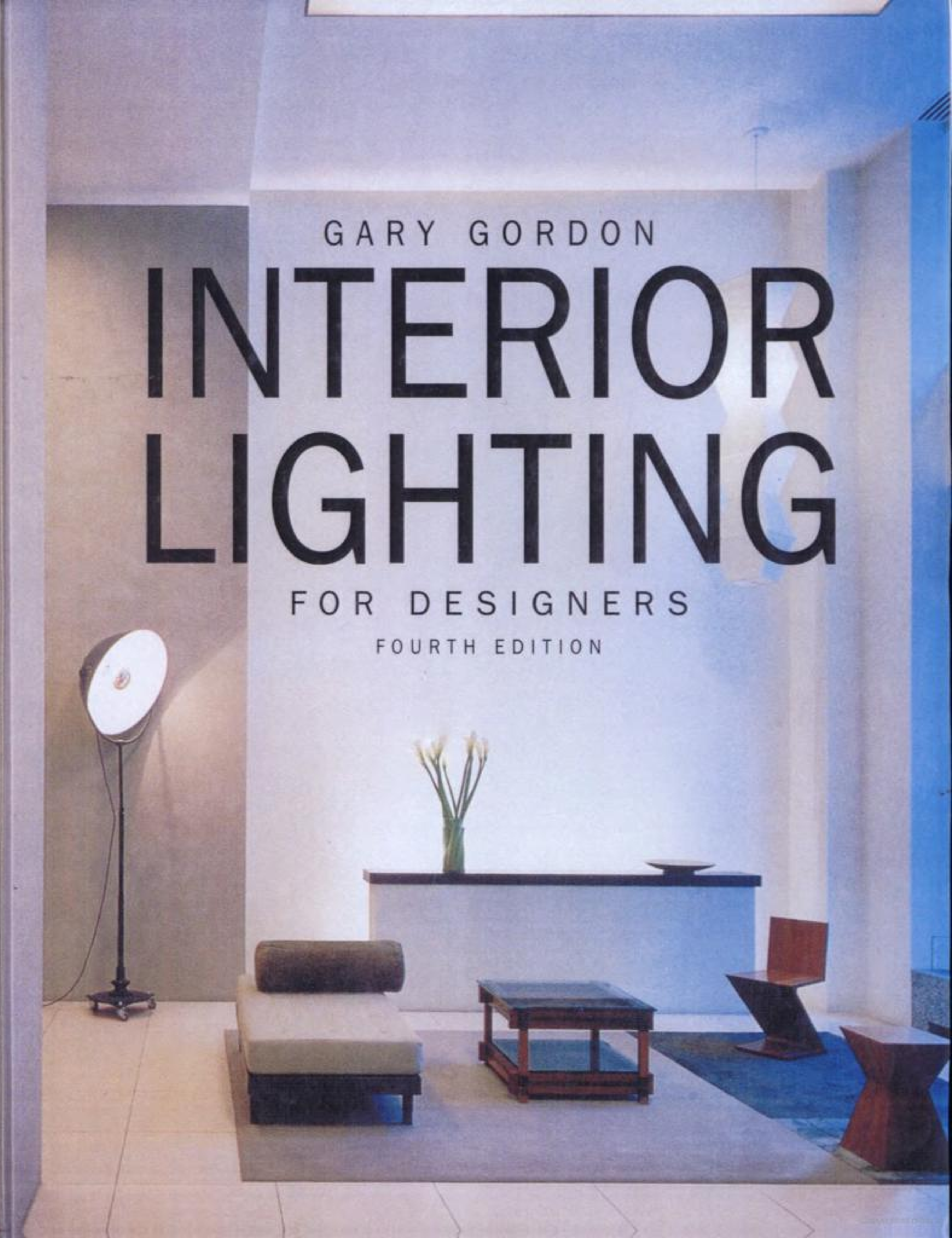
GARY GORDON

INTERIOR LIGHTING

FOR DESIGNERS

FOURTH EDITION



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Gary Gordon FIES, FIALD, LC

Illustrations by Gregory F. Day

John Wiley & Sons, Inc.

Interior Lighting for Designers

About the cover photograph: The developer of this midtown-Manhattan residential tower wanted to lure young, affluent apartment seekers to a less-than-glamorous neighborhood. He relied on architecture to do it. The lighting concept reinforces the architect's asymmetrical, "anti-classical" approach: there is no traditional bottom-middle-top. The white, plaster wall is lighted with floor-mounted 100PAR/HIR lamps 12" on center. A rough, industrial, Italian, factory floor lamp is paired with a soft, Japanese, paper-shade pendant to contribute to the residential scale. The building fully rented six months after the lobby's completion, 18 months ahead of schedule.

Gary Gordon received the 2000 Illuminating Engineering Society Lumen Award and the 2000 International Illuminating Design Award for this project. The New Gotham Lobby, Stephen Alton Architects. Photo by Eduard Hueber.

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For

my grandfather,

Louis Becker,

who first inspired me to look at buildings

Contents

Preface to the Fourth Edition

This Fourth Edition expands upon the foundation established in the previous edition, with the added benefit of greater clarity throughout. While it retains the mark of the thorough copy and technical edit provided for the Third Edition by the late luminaire-design genius Edison Price, chapters 9, 10, and 11 have been reorganized to correspond more closely with professional practice. New to this edition is material on the latest advances in lighting technology and practice; state-of-the-art light sources, equipment, and systems; and a comprehensive glossary. For the first time, an Instructor's Manual is available on-line from the publisher to accompany the text.

As with the Third Edition, this book is intended to serve as both a textbook for architecture and interior design students and a manual for practicing professionals. It provides a simple framework for understanding the lighting design process. More than 250 line drawings, photographs, and color plates, many of them new to this edition, illustrate the text. The design of light for interiors is emphasized; tools and techniques are presented as a means by which to achieve the design. This is an architectural approach to lighting design, based on my apprenticeship with the talented architect and lighting designer Carroll Cline, as well as twenty years of professional practice.

The lighting design process outlined in this book parallels the methodology used by lighting professionals to provide solutions for architectural interiors around the world. I developed this system for describing the lighting design process while teaching graduate and undergraduate students at the Parsons School of Design Lighting Institute in New York City. The success of this method is demonstrated by the great number of my former students who professionally practice lighting design today.

ACKNOWLEDGMENTS

This work owes an enormous debt to Caryl Gordon and Mary Hebert for their help with copy-editing and proofreading; to Dr. Kevin Houser for his exceptionally thorough technical edit; and to David Marini for his assistance with the layout and design.

Valuable research assistance was provided by the able crew of the Gary Gordon LLC office in New York: Kevin Frary, Justin Horvath, Michael Haslam, Christine Kong, Ryan Stromquist, Rob Thomas, and Ryan Wither. Rob Thomas skillfully coordinated all of the drawings, color plates, and photographs.

I am also grateful for the support of Aneeahseah Lefler and Jennifer Downey. At John Wiley & Sons, Amanda Miller provided editorial guidance, and Jennifer Ackerman made working on this book a joy.

Gary Gordon FIES, FIALD, LC
New York, New York
September 2002

Introduction

Lighting design is a process. It is the process of integrating light into the fabric of architecture. Regardless of the space to be lighted—a bank, a church, an office, a gallery, a restaurant, a store, a classroom—and regardless of the light sources available for use, the process is always the same.

Because lighting design is a process, it can be learned. This book traces the steps in the lighting design process much as a professional performs them in practice. Design, of course, is not always a linear process. At times some of these steps are used simultaneously. But, on the whole, the order of the material corresponds to professional practice.

This book does not describe *the* lighting design process; it describes *a* lighting design process. It is one that has been used successfully by Gary Gordon LLC to provide solutions for more than one thousand architectural projects around the world. It is a process built on the conviction that the lighting condition of a space has enormous emotional impact on people.

A common mistake when providing light for buildings is to select the lighting equipment first. Selecting luminaires is the last step in the process. What is important is not what makes the light, but which objects and surfaces receive it. The key to successful lighting design is to decide *what* you want to light first, and then work backward to determine the solution.

In chapter 1, we learn by understanding the human visual system that perception of the world around us is based not on the quantity of light entering the eye but on the quantity of contrast. In chapter 2, we learn from psychology that because the sense of sight is contrast-sensitive, the brightness contrast of a space determines its emotional impact. In chapter 3, we learn how the direction and distribution of light determine the brightness contrasts that yield the desired emotional setting.

Once the emotional setting and brightness contrast have been established, we begin our selection of light sources by determining the color of light in chapter 4. The next three chapters provide a thorough knowledge of light sources, from daylight (chapter 5) through incandescent and tungsten-halogen (chapter 6) to discharge sources: fluorescent, mercury, metal halide, and high-pressure sodium (chapter 7). Chapter 8 describes the auxiliary equipment required to operate discharge and low-voltage incandescent lamps.

Chapter 9 explains the external devices employed to modify light sources so that they provide the desired direction and distribution of light and control glare. With the light source modified, Chapter 10 illustrates how we use photometry to predict the quantity of light in completed space. Chapter 11 provides an understanding of the electrical requirements of light sources and methods of lighting system control.

Once the source, with its external devices, methods of modifying distribution and controlling glare, and electrical requirements, is established, we are at last ready to select the luminaire in chapter 12. It is only at this point in the lighting design process that a suitable luminaire can be chosen: after the designer has identified the activity in a space and degree of contrast required, and has determined the color of light, light sources, modifications to control source distribution and glare, and locations of light sources.

Our final chapter looks at the elements that produce visual clarity; design techniques for lighting architectural surfaces, tasks, and art; the balance of brightness; energy-effective design; and integrating light and architecture.

The architectural lighting design process described in this book produces a space where the casual observer is unaware of the mechanics of light production; he perceives only a comfortable environment that supports his activities and enhances his well-being. With practice, the designer learns to apply this process in ways that go even further, producing environments that stimulate the mind and inspire the spirit.

Perception

1

Perception of the world around us is based not on the quantity of light entering the eye, but on the quantity of contrast.

VISIBLE LIGHT

What we perceive as light is a narrow band of electromagnetic energy, ranging from approximately 380 nanometers (nm) to 760 nm. Only wavelengths in this range stimulate receptors in the eye that permit vision (figure 1.1 and color plate 1). These wavelengths are called *visible energy* even though we cannot directly see them.

In a perfect vacuum, light travels at approximately 186,000 miles per second. When light travels through glass or water or another transparent substance, it is slowed down to a velocity that depends on the density of the medium through which it is transmitted (figure 1.2). This slowing down of light is what causes prisms to bend light and lenses to form images.

When light is bent by a prism, each wavelength is refracted at a different angle so the emergent beam emanates from the

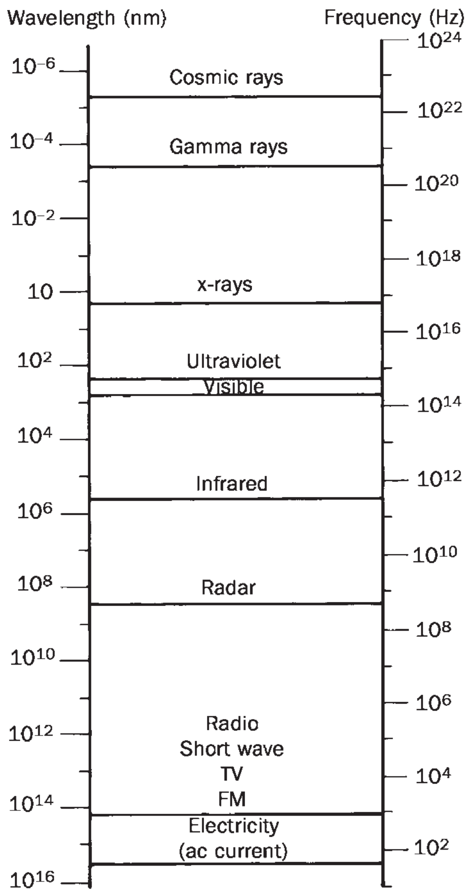


Figure 1.1 Visible light is a narrow region of the total electromagnetic spectrum, which includes radio waves, infrared, ultraviolet, and x-rays. The physical difference is purely the wavelength of the radiation, but the effects are very different. Within the narrow band to which the eye is sensitive, different wavelengths give different colors. See also color plate 1.

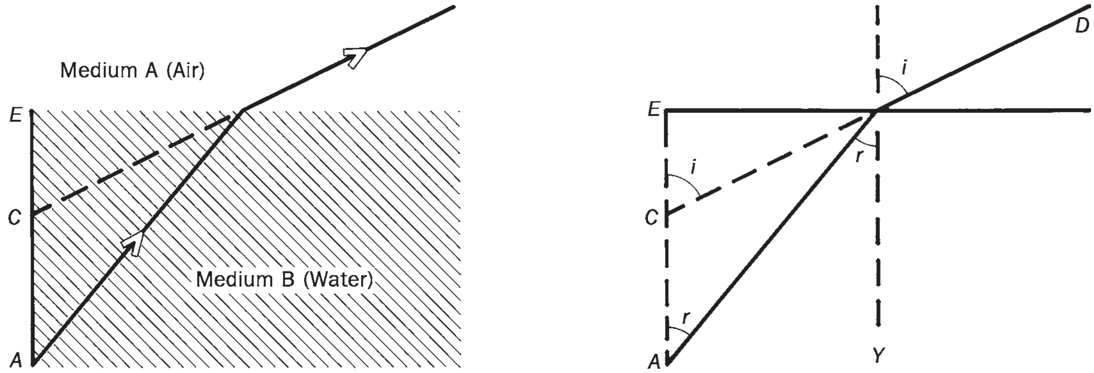


Figure 1.2 The law of refraction (Snell's law) states that when light passes from medium A into medium B the sine of the angle of incidence (*i*) bears a constant ratio to the sine of the angle of refraction (*r*).

prism as a fan of light, yielding all of the spectral colors (see color plate 2).

All electromagnetic radiation is similar. The physical difference between radio waves, infrared, visible light, ultraviolet, and x-rays is their wavelength. A *spectral color* is light of a specific wavelength; it exhibits deep chromatic saturation. *Hue* is the attribute of color perception denoted by what we call red, orange, yellow, green, blue, and violet.

THE EYE

A parallel is often drawn between the human eye and a camera. Yet visual perception involves much more than an optical image projected on the retina of the eye and interpreted "photographically" by the brain.

The human eye is primarily a device that gathers information about the outside world. Its focusing *lens* throws a minute inverted image onto a dense mosaic of light-sensitive receptors, which convert the patterns of light energy into chains of electrical impulses that the brain will interpret (figure 1.3).

The simplest way to form an image is not with a lens, however, but with a pinhole. In figure 1.4, a ray from each point of the object reaches only a single point on the

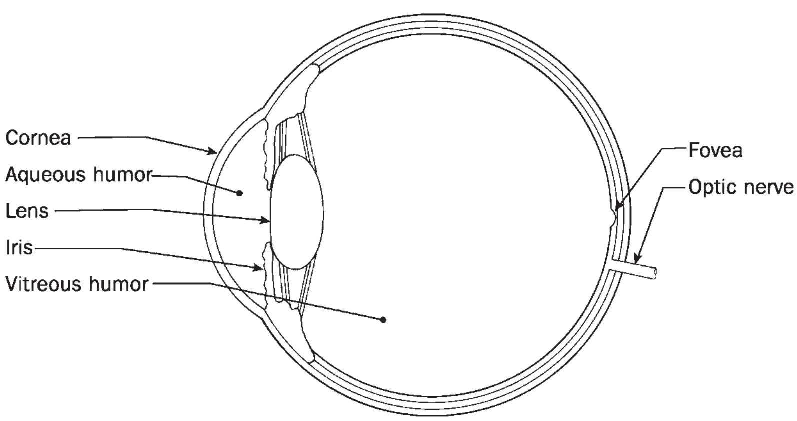


Figure 1.3 Cross section of the human eye.

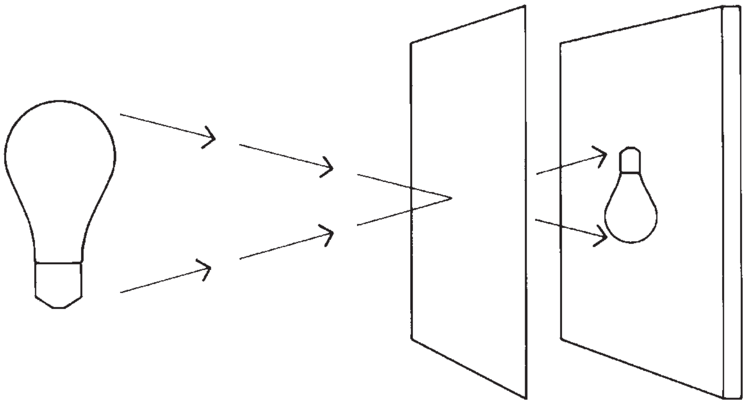


Figure 1.4 Forming an image with a pinhole.

screen, the two parts being connected by a straight line passing through the pinhole. Each part of the object illuminates a corresponding part of the screen, so an upside-down image of the object is formed. The pinhole image is dim, however, because the hole must be small (allowing little light to pass through) if the image is to be sharp.

A lens is able to form a much brighter image. It collects a bundle of light rays from each point of the object and directs them to corresponding points on the screen, thus giving a bright image (figure 1.5).

The lens of the human eye is built up from its center, with cells being added all through life, although growth gradually slows down. The center is thus the oldest part, and as the cells age they become more compact and harden. As a result, the lens stiffens and is less able to change its shape to accommodate varying distances (*presbyopia*) (figure 1.6).

Lenses work well only when they fit properly and are adjusted correctly. Sometimes the lens is not suited to the eye in which it finds itself: (1) the lens focuses the image in

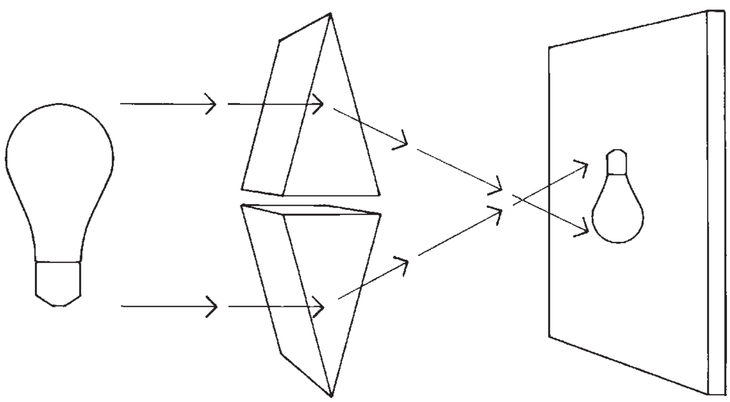


Figure 1.5 Forming an image with a lens. The lens shown is a pair of prisms; image-forming lenses have curved surfaces.

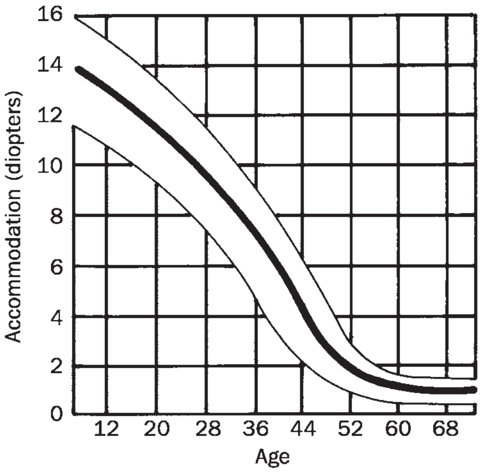


Figure 1.6 Loss of accommodation of the lens of the eye with aging.

front of or behind the retina instead of on it, giving "short" sight (nearsighted or *myopic*) or "long" sight (farsighted or *hyperopic*); (2) the lens is not truly spherical, giving distortion and, in some directions, blurring of the image (*astigmatic*); or (3) the cornea is irregular or pitted.

Fortunately, almost all optical defects can be corrected by adding artificial lenses, which we call *eyeglasses.* Eyeglasses correct for errors of focus (called *accommodation*) by changing the power of the lens of the eye; they correct for distortion (called *astigmatism*) by adding a nonspherical component. Ordinary glasses do not correct damage to the surface of the cornea, but *corneal lenses*, fitted to the eye itself, serve to give a fresh surface to the cornea.

The *iris* is the pigmented part of the eye. It is found in a wide range of colors, but the color has no impact on vision as long as it is opaque. The iris is a muscle that forms the *pupil*. Light passes through the pupil to the lens which lies immediately behind it. This muscle contracts to reduce the aperture of the lens in bright light and also when the eyes converge to view near objects.

The *retina* is a thin sheet of interconnected nerve cells, which include the light-sensitive cells that convert light into electrical impulses. The two kinds of light-receptor cells—*rods* and *cones*—are named after their appearance as viewed under a microscope (figure 1.7).

Until recently, it was assumed that the cones function in high *illuminance*, providing color vision, and the rods function under low illuminance, yielding only shades of gray. Color vision, using the cones of the retina, is called *photopic*; the gray world given by the rods in dim light is called *scotopic*.

Recent research, however, suggests that both rods and cones are active at high illuminance, with each contributing to different aspects of vision. When both rods and cones are active, vision is called *mesopic*.

THE BRAIN

The eyes supply the brain with information coded into chains of electrical impulses. But the "seeing" of objects is determined only partially by these neural signals. The brain searches for the best interpretation of available data. The perception of an object is a hypothesis, suggested and tested by sensory signals and knowledge derived from previous experience.

Usually the hypothesis is correct, and we perceive a world of separate solid objects in a surrounding space. Sometimes the evaluation is incorrect; we call this an *illusion.* The ambiguous shapes seen in figures 1.8 and 1.9 illustrate how the same pattern of stimulation at the eye gives rise to different perceptions.

BRIGHTNESS PERCEPTION

We speak of light entering the eye, called *luminance*, which gives rise to the sensation

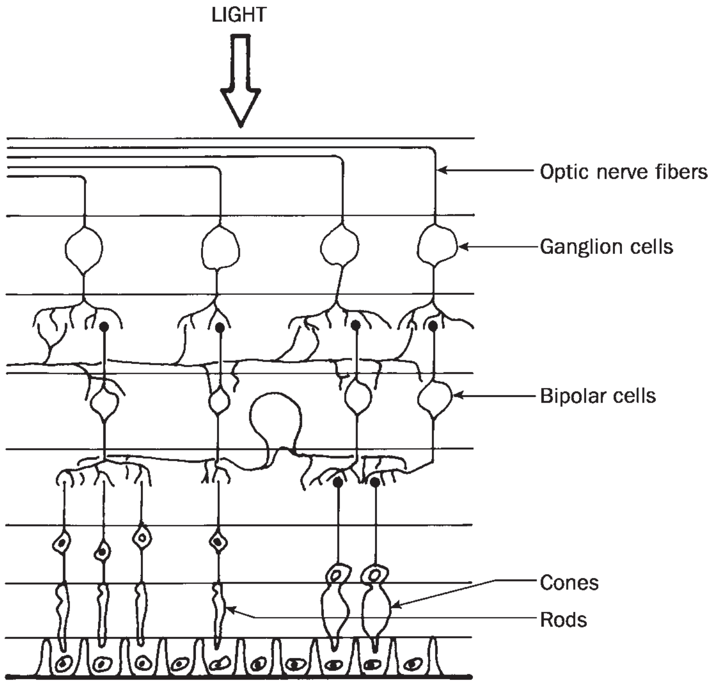


Figure 1.7 The retina.

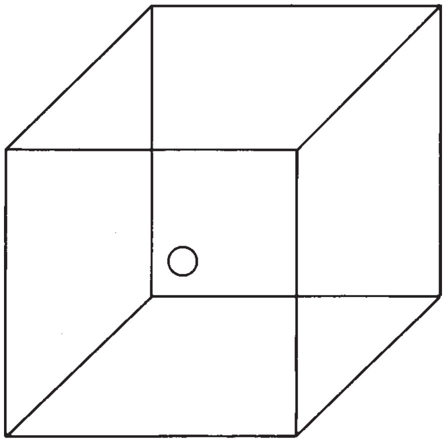


Figure 1.8 Necker cube. When you stare at the dot, the cube flips as the brain entertains two different depth hypotheses.

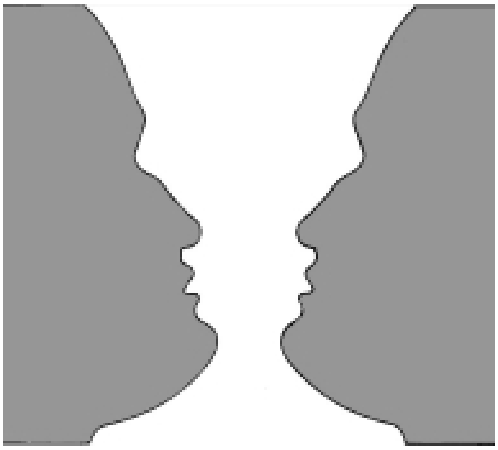


Figure 1.9 Ambiguous shapes. Is it a vase or two faces in profile?

of *brightness*. Illuminance, which is the density of light received on a surface, is measured by various kinds of photometers, including the familiar photographer's exposure meter.

Brightness is a subjective experience. We hear someone say, "What a bright day!" and we know what is meant by that. But this sensation of brightness can be only partly attributed to the intensity of light entering the eyes.

Brightness is a result of: (1) the intensity of light falling on a given region of the retina at a certain time, (2) the intensity of light that the retina has been subject to in the recent past (called *adaptation*), and (3) the intensities of light falling on other regions of the retina (called *contrast*).

Figure 1.10 demonstrates how the intensity of surrounding areas affects the perception of brightness. A given region looks brighter if its surroundings are dark, and a given color looks more intense if it is surrounded by its complementary color.

If the eyes are kept in low light for some time they grow more sensitive, and a given quantity of light will seem brighter. This "dark adaptation" is rapid for the first few seconds, then slows down. As the eye becomes dark adapted, it loses *acuity* while it gains sensitivity. With a decrease of intensity and the compensating dark adaptation, the ability to make out fine detail is lost.

The cone and rod receptor cells adapt at different rates: cone adaptation is completed in about seven minutes; rod adaptation continues for an hour or more. This is demonstrated by the difference between leaving a dark movie theatre and emerging into bright daylight (cone or light adaptation), and its reverse: entering a dark theatre from a bright, sunny day (rod or dark adaptation).

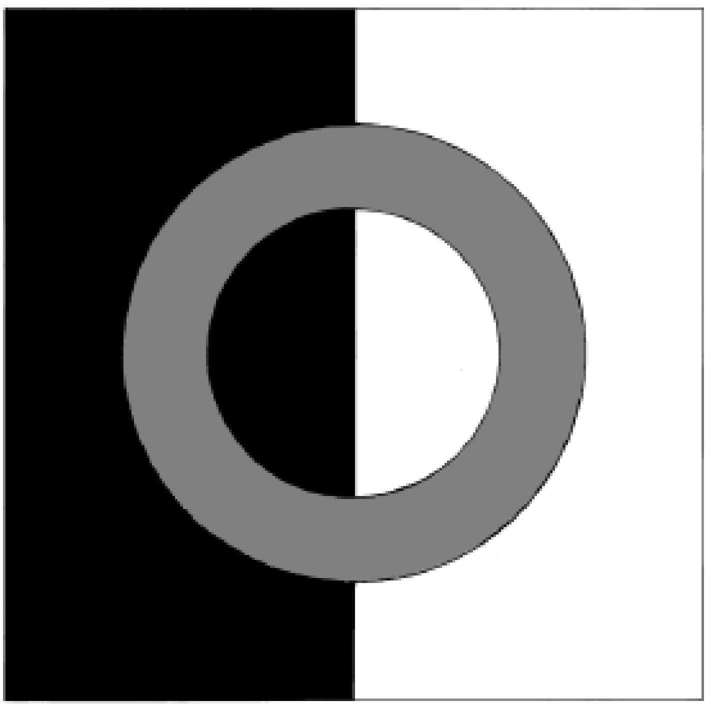


Figure 1.10 Simultaneous contrast.

COLOR PERCEPTION

Brightness is also a function of color. For a given intensity, the colors at the middle of the spectrum look brighter than those at the ends. The sensitivity curves for rods and cones are different. Their shape is similar, but the cones are most sensitive to yellow, and the rods are most sensitive to green. This change with increasing intensity is known as the *Purkinje Shift* (figure 1.11).

The visible spectrum is comprised of five colors of light (see color plate 3) (not of pigment [see color plate 4]): violet, blue, green, yellow, and red. These colors can be mixed: for example, yellow is obtained by combining red with green light.

Mixing colors of light is achieved by using filters, prisms, or diffraction gratings. By mixing two colors of light, a third color is formed in which the two mixed colors cannot be identified.

By mixing three colors of light and adjusting their intensities, any spectral hue can be produced. White can be made, but not black or nonspectral colors such as brown (see color plate 3).

When speaking technically about color vision, we do not refer to "colors" but rather to "hues." This is to avoid difficulty with the term colors, which is descriptive of the physiological sensations to which we give specific names, such as "red" or "blue." We therefore speak technically of spectral hues rather than spectral colors.

Another important distinction is to be found between color as a *sensation* and color as a *wavelength* (or a set of wavelengths) of light entering the eye. Technically, light itself is not colored: it gives rise to sensations of brightness and color, but only in conjunction with a suitable eye and nervous system. When we speak of "yellow light," it means light that gives rise to a sensation described by the majority of people as "yellow."

All the colors of the spectrum are interpreted by the brain from only three kinds of receptors in the eyes: violet, green, and red. These three kinds of color-sensitive receptors (cones) respond to blue-violet, pure green, and orange-red; all colors are "seen" by a mixture of signals from the three systems.

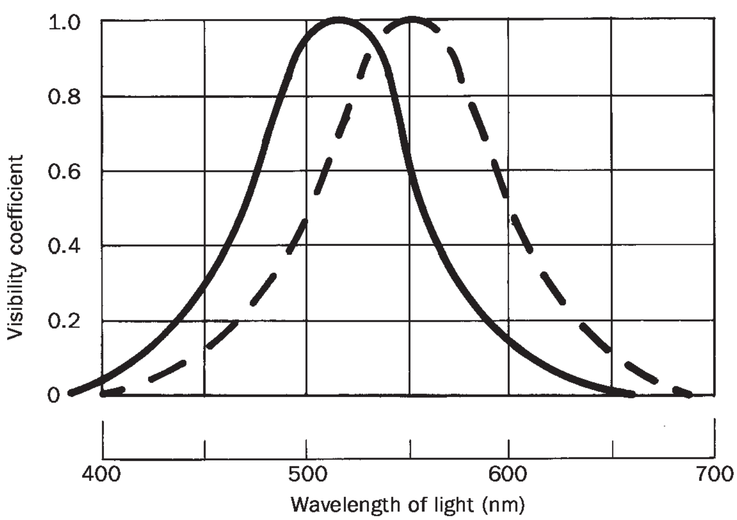


Figure 1.11 The Purkinje Shift.

What we perceive as white is not a particular mixture of colors, but rather the general illumination, whatever this is. A candle or lamplight that looks white by itself appears yellow when “white” electric light or daylight is present for comparison.

The reference for what is taken as white shifts. Knowledge of the normal color of objects is called *color constancy*; it leads us to expect that a tomato will be red. The brain’s stored knowledge and expectations exert a strong influence on color perception: objects such as oranges and lemons, for example, take on a richer color because they are recognized as orange and yellow.

Grass is a plant found on lawns and we call the sensation of color it gives “green,” but we identify grass by characteristics other than its color: its presence as a lawn, the form and density of the blades, and so forth. If we do confuse the color, sufficient additional evidence is available to identify it as grass. We know it is supposed to be green and we call it green, even when this is doubtful as in the dim light of dusk.

In 1992, neurophysiologists discovered that an alignment of brain cells forms the basis of visual memory. The cells are stacked in columns; depending on which columns are excited by an object, the brain is able to instantly recognize complex images such as faces, even when presented at odd angles or when only part of the face is visible.

Yet it remains a mystery how the contributions from separate channels for brightness, color, shape, and movement—with their own locations in different regions of the brain—come together to form consistent perceptions.

THE SENSE OF SIGHT

We do know that perception is independent of the quantity of light entering the eye; it is based on the quantity of contrast: the differences between light and dark. A certain quantity of light is necessary for a person to see, yet the eye responds not to the total intensity, but to the average intensity in the field of view.

The sense of sight, therefore, is contrast sensitive. It is a mechanism for the detection of differences: of figures on a ground, of objects in a surround. Subjective impressions of space are a function of the degree of contrast present in the environment.

Psychology 2

Because the sense of sight is contrast sensitive, the brightness contrast of a space determines its emotional impact.

EMOTIONAL IMPACT

Subjective impressions of space are a function of brightness contrast: the relationship of surfaces that are lighted (the focus or foreground) to those that are left in comparative darkness (the surround or background). It is possible, of course, to simply introduce general illumination into a room to permit vision. But establishing the emotional impact of an interior through the manipulation of brightness contrast is the real challenge for the creative designer.

Reliance on published standards for illuminance on the *workplane* leads unintentionally to environments that are sterile and unstimulating. Proper attention to the manipulation of brightness contrast as a principal technique for the design of lighting systems results in environments that are inviting, inspiring, and supportive of the tasks to be performed.

If all objects and surfaces in a room receive equal emphasis from light, contrast is lost. Over time, the lack of contrast causes people to feel listless and depressed. Without contrast, the environment produced has the quality of a cloudy, overcast day.

People feel more alert, energetic, and positive on a sunny day, which is marked by bright highlights and crisp shadows. By providing brightness contrast, an environment may be created that has the attributes of a sunny day. In truth, the significant difference between a “dull, dreary day” and a “bright, cheerful” one is the quality of light.

DEGREES OF STIMULATION

Some activities and tasks benefit from a high degree of stimulation to encourage participation and increase enjoyment. Other activities and tasks benefit from a minimum of contrast to help a person feel contented, comfortable, focused, and relaxed. Although individuals react differently to the same environment, there is a high degree of similarity in people’s reactions to light.

Environmental psychologists use the terms *high-load* and *low-load* to describe degrees of stimulation or arousal. The more stimuli that must be processed by a person, the higher the load. Environments that are complex, crowded, asymmetrical, novel, unfamiliar, surprising, or random are high load. Environments that are simple, uncrowded, symmetrical, conventional, familiar, unsurprising, or organized are low-load.

If the task to be performed is complex or unusual—studying technical material, preparing for an exam, or writing an essay—the load is great enough that our degree of arousal is fairly high; additional load from the environment will increase stimulation to such a point that the task is avoided. We become distracted, annoyed, or frustrated, and performance falls off sharply.

Tasks that are simple or routine—writing checks, making a shopping list, or other familiar chores—benefit from a mildly stimulating environment. Daydreaming or dozing may result without increased stimulation. This is why such work often fails to be performed in home offices or studies designed for paperwork; instead it is done in kitchens, dining rooms, or living rooms, which have a higher degree of stimulation.

The lower the load of the task, the more it requires a high-load setting for optimum performance. Boring tasks are boring because they are unstimulating (simple or overly familiar) and often unpleasant. Within reason, the more stimulation provided, the more pleasant the task becomes. For many, basic housework is monotonous; playing background music increases stimulation, enabling us to complete "boring" domestic chores.

DEGREES OF BRIGHTNESS CONTRAST

The degree of brightness contrast evokes emotions in the same way as background music. It affects the performance of tasks, influences the behavior of people at work and at play, and impacts the amount of contentment and pleasure we experience. The degree of brightness contrast establishes the emotional setting, which either reinforces or undermines the intended activity.

The first step in the lighting design process is to identify the activity that will occur in a space. The second step is to determine a degree of stimulation that will reinforce that activity. The third step is to establish the degree of brightness contrast that will yield the necessary level of stimulation.

Brightness contrast is established by developing patterns of light and shade—by selecting specific surfaces and objects to receive lighting emphasis while leaving others in comparative darkness. This emphasis creates the relationship between foreground and background (figure 2.1).

Low-Contrast Environment

If everything is to receive equal emphasis, no hierarchy is established between foreground and background. The result is a *low-contrast* environment. Low-contrast spaces are low in stimulation: few stimuli exist to respond to. These spaces are behaviorally neutral (figure 2.2).

A large proportion of *diffuse* light and a small amount of *focused* light produce this low-contrast environment. Low-contrast lighting systems are intended to provide easy seeing for visual tasks, to allow random circulation, or to permit flexible relocation of work surfaces. The diffuse lighting technique provides a uniformly illuminated working environment, an area suitable for difficult and sustained visual tasks (figure 2.3).

Lighting systems that flood a space with diffuse light from overhead reduce contrast. Highly diffuse light produces a shadowless environment; forms are ill-defined and textural perception is poor. Although this is adequate for task vision, it ignores the problem created by the bland psychological reaction to a cloudy day.

Figure 2.1 Patterns of light and shade establish brightness contrast.

Figure 2.2 Low-contrast lighting.

Figure 2.3 Low-contrast lighting.

High-Contrast Environment

A small proportion of diffuse light and a large amount of focused light produce a *high-contrast* environment. High-contrast lighting systems render patterns of light and shade; they intentionally establish a hierarchy between foreground and background. High-contrast spaces increase stimulation; they are intended to evoke specific moods or emotions (figure 2.4).

A single spotlight on a stage is an extreme example of the influence of brightness contrast in creating focal points. A room lighted in this way dominates the people in it; the brightness contrast directs their attention and holds their interest, producing visual direction and focus (figure 2.5).

Attention is involuntarily drawn toward areas of brightness that contrast with the visual background. When a person approaches an unfamiliar space or activity, brightness contrast and color contrast help to establish an initial response. High-contrast environments are useful for guiding the circulation of people entering an unfamiliar room.

THE THREE ELEMENTS OF LIGHT

The three fundamental elements of light are: ambient light, focal glow, and sparkle. The ratio of ambient light to focal glow establishes the degree of brightness contrast in a space; sparkle adds the highlights that contribute to feelings of well-being. The proportions of these three elements yield the desired emotional setting.

The late lighting designer Richard Kelly poetically defines the three elements of light. To Kelly, ambient or general light is

> a snowy morning in open country . . . twilight haze on a mountain top or a cloudy day on the ocean . . . the light in a white tent at noon . . . moonlight coming through the fog.

Figure 2.4 High-contrast lighting.

Figure 2.5 High-contrast lighting.

> Ambient luminescence is shadowless illumination. It minimizes form and bulk. It dematerializes. It reduces the importance of things and people. It fills people with a sense of freedom of space and suggests infinity. It is usually reassuring and restful.
>
> The best example is a foggy day on a mountain top. There is an even glow without incidence all around; there are no shadows, nothing to tell you what to look at. In that sense it's confusing, but it is also relaxing and restful, as there is no excitement, no interest. It minimizes man—think about a figure moving through that fog—and destroys form [figure 2.6].

Figure 2.6 Ambient luminescence.

Focal glow or task light, for Kelly, is

> the campfire of all time, the glowing embers around which stories are told, or the football rally bonfire. Focal glow is the limelight, the follow spot on the stage, and an aircraft beacon. . . . It is the light burning at the window or the welcoming gleam of the open door.
>
> Focal glow is the sunburst through the clouds and the shaft of sunshine that warms the far end of the valley. It is the pool of light at your favorite reading chair, your airplane-seat light, or match-light on a face. Focal glow is the end of the rainbow; it commands attention, creates interest, fixes the gaze, and tells people what to look at. Focal glow is the focus. It separates the important from the unimportant, establishes precedence, can induce movement, and can control traffic.
>
> Focal light is directive, creates a bright center; it tells us what to look at, organizes, marks the most important element. It creates a sense of space; you can organize depth through a sequence of focal centers [figure 2.7].

To Kelly, sparkle or glitter is:

> a play of brilliants . . . the sensation of a cache of diamonds in an opened cave or the Versailles Hall of Mirrors with its thousands of candle flames . . . a ballroom of crystal chandeliers. Play of brilliants is Times Square at

Figure 2.7 Focal glow.

night . . . sunlight on a tumbling brook . . . the heaven full of stars . . . birch trees interlaced by a motor car's headlights.

Play of brilliants excites the optic nerves . . . stimulates the body and spirit and charms the senses. It creates a feeling of aliveness, alerts the mind, awakens curiosity, and sharpens the wits. It quickens the appetite and heightens all sensations. It can be distracting or it can be entertaining.

Sparkle is scintillation. It is a tiny microscopic bombardment of points of light—the most exciting kind of light there is. It stimulates and arouses appetites of all kinds; chandeliers in dining rooms, sequins on dresses, and lights on theatre marquees all take advantage of the fact[1] [figure 2.8].

Outdoors, during daytime, the sky provides the ambient light. Objects and surfaces that are illuminated by the sun, such as a meadow, trees, or the side of a building, are the focal glow. The reflection of the sun from *specular* surfaces, such as moving water, dew on leaves, or polished metal on a building, supplies the sparkle.

At the beach, the ambient light provided by the sky is balanced by the diffuse,

[1]John Marsteller, "A Philosophy of Light: Recalling Richard Kelly's Three Functional Elements," *Interior Design* February 1987: 78–80.

Figure 2.8 Sparkle.

reflected light from the sand. Objects that are lighted by the sun, such as sandcastles, people, bright beach blankets, and bathing suits, become the focus. The glistening of the sun on the agitated water or on wet stones at the water's edge is the sparkle.

Indoors, the proportions of these same elements—ambient light, focal glow, and sparkle—always and everywhere determine the emotional setting.

SUBJECTIVE IMPRESSIONS

The late professor John Flynn documents that as patterns of brightness contrast change, the strength of visual stimuli also changes, altering our impressions of space.

While looking for evidence that lighting changes alone elicit significantly different reactions, Flynn tested six lighting schemes without making other changes in the room (figures 2.9 to 2.14). These changes in lighting condition evoke consistent responses in three areas of impression: spaciousness, perceptual clarity, and pleasantness.

Impressions of spaciousness

The impression of a room's largeness or smallness is affected by the intensity and uniformity of the lighting at the room perime-

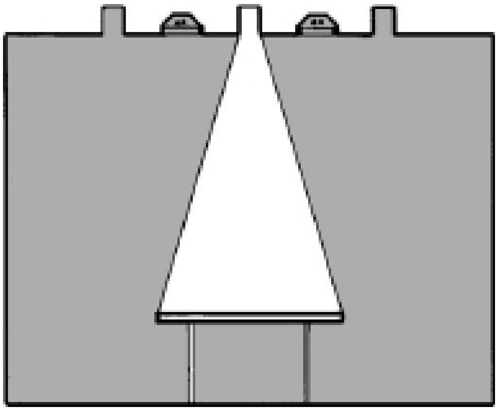


Figure 2.9 Overhead downlighting, low intensity.

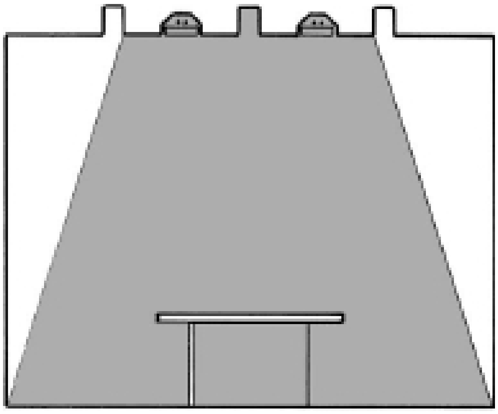


Figure 2.10 Peripheral wall lighting, all walls.

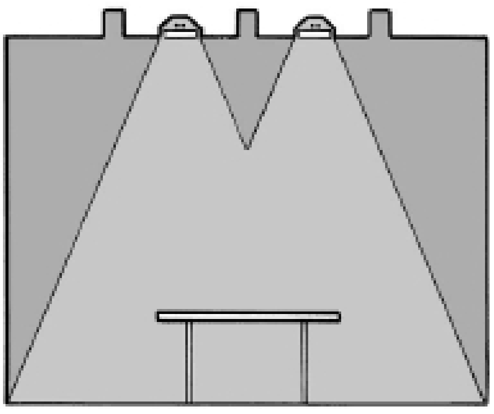


Figure 2.11 Overhead diffuse lighting, low setting.

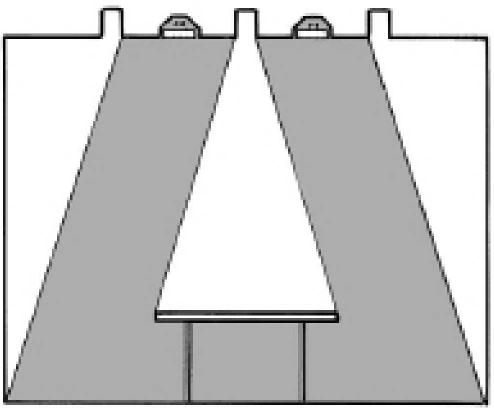


Figure 2.12 Combination: overhead downlighting + end walls.

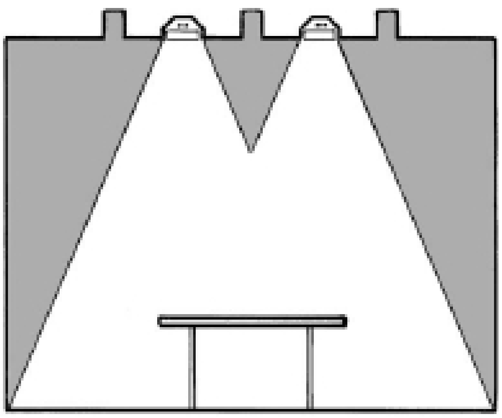


Figure 2.13 Overhead diffuse lighting, high intensity.

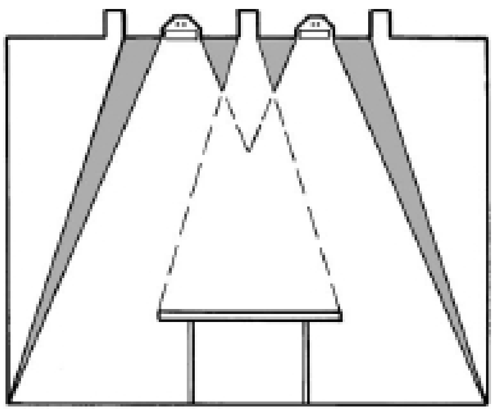


Figure 2.14 Combination: overhead downlighting, overhead diffuse lighting, + end walls.

Figure 2.15 Impressions of spaciousness (large-small).

ter. Flynn found that differences in quantity of horizontal illuminance significantly alter impressions of spaciousness and perceptual clarity. Higher illuminance values are described as "clear," "bright," "distinct," "large," and "more spacious"[2] (figure 2.15).

[2]Improvement in visual contact continues to approximately 25 footcandles (fc) of ambient horizontal illuminance, beyond which it stabilizes.

Impressions of perceptual clarity

Nothing is more important than how people's faces appear. Flynn demonstrated that lighting schemes rated high in facial clarity are considered more public; schemes that are rated low in facial clarity are considered more private.

Public space implies intermingling and bringing people together. The potential for visual contact improves as the intensity of

Figure 2.16 Impressions of perceptual clarity—public space.

Figure 2.17 Impressions of perceptual clarity—private space.

general illuminance is increased. Increasing intensities reduce anonymity and bring people together because facial expressions and gestures are more clearly perceptible (figure 2.16).

Private space suggests separating people and keeping them apart. Shadow and silhouette reinforce feelings of detachment and privacy because these lighting techniques inhibit the ability to perceive precise facial detail; even nearby individuals become more anonymous (figure 2.17).

In a crowded space, when it is impossible to separate people physically by distance, it is possible to separate them visually by lighting. This technique is often used in cocktail lounges, fine restaurants, and reception rooms.

Impressions of pleasantness

Flynn also found that the nonuniform brightness produced by a downward concentrating lighting system rates more favorably than the uniform brightness produced by a diffuse system. The nonuniform brightness is rated as more “friendly,” “pleasant,” “sociable,” and “interesting” (figure 2.18). Differences in the quantity of horizontal illuminance from overhead systems exert negligible influence on impressions of pleasantness.

Figure 2.18 Impressions of pleasantness.

Vertical Surface Illumination

When wall lighting is added, Flynn discovered that ratings shift to the positive for all three categories of impression. Lighted vertical surfaces reinforce feelings of spaciousness, clarity, and pleasantness.

VARIATION

Lack of variation in the built environment is an obstacle that lighting helps to overcome. Monotony results in boredom and depression: even a string of bright, sunny days will become boring through overfamiliarity. Variation increases stimulation and impressions of pleasantness.

One way to increase the load of office or factory environments is to introduce stimuli that vary over time; otherwise, workers quickly become accustomed to the setting. For example, areas for coffee and lunch breaks that have greater contrast and sparkle than the workplace introduce variety through a change of the lighting condition, while also encouraging sociability and conversation.

People using a library, as those in the office and factory, benefit from more stimulating lighting systems in areas used for taking breaks, socializing, or simply daydreaming, for relief from the fatigue caused by concentrated work. The typical library has quiet stacks and cubicles conducive to study, and other areas for relaxed reading and scanning periodicals. People prefer less loaded settings for difficult, complex materials, and more loaded spaces for casual, pleasant reading.

If workers are performing complex and dangerous tasks, however, a pleasant low-load lounge lowers their degree of stimulation. Conversely, performance of low-load tasks in dull settings benefits enormously from pleasant and mildly stimulating diversions. If you must wade through low-load paperwork, such as reading reports, reviewing dull proposals, or composing routine correspondence, productivity is increased when offices are provided with a means of altering the lighting condition.

A fixed, ideal lighting solution that will increase performance while a person is doing a monotonous task is unattainable. Changing all the lamps in a factory to an improved-color light source is insufficient, for example; in time, such a static modification loses much of its stimulating value. A controllable variability of the lighting environment is necessary and beneficial.

In addition to the lighting system, surface finishes, textures, and colors also contribute to the environmental load. In practice, they all must be considered at the same time.

Brightness 3

Specifying the direction and distribution of light in a space yields the desired brightness contrast.

Brightness versus luminance
Brightness is the subjective sensation that occurs in the consciousness of a human observer. *Luminance* is the objective measurement of intensity per unit of projected area.

DIRECTION AND DISTRIBUTION OF LIGHT

A *luminaire* (lighting fixture) emits light in one of three directions—downward, upward, or multidirectional—and in one of two distributions—concentrated or diffuse (figure 3.1).

Downward light from a properly designed luminaire has a restricted angular spread; *direct glare* is prevented by both this restricted spread and the shape of the human eyebrow. *Upward* light usually covers a large area of the ceiling; the light reflected from the ceiling is of low luminance and is unlikely to cause distracting glare. *Multidirectional* light is emitted in all directions, but it cannot emit much of its output sideways without causing objectionable glare.

Upward and downward light is emitted in patterns that vary from narrow to wide. *Concentrated* distribution focuses light in a narrow pattern; *diffuse* distribution disperses light in a wide pattern.

Luminaires with narrow *beam-spreads* that lack an upward component of light produce a *concentrated downward* (also called *direct*) distribution (figure 3.2). When located in low ceilings, concentrated downward beams—with spreads of 30° or less—create areas of high luminance on the floor with dark areas in between. To avoid this unevenness, luminaires would need to be placed inordinately close to each other. Low ceilings require the use of diffuse downward luminaires.

When located in high ceilings, concentrated downward beams overlap and avoid such light and dark areas, yet only horizontal surfaces and the tops of objects are lighted; faces and walls receive little light and appear in shadow. This yields a high-contrast space, one of low ambient brightness with high brightness accents (figure 3.3).

Luminaires with diffuse beam-spreads and a downward distribution produce *diffuse downward* (*direct*) light (figure 3.4). Diffuse downward beams—with spreads from 80° to

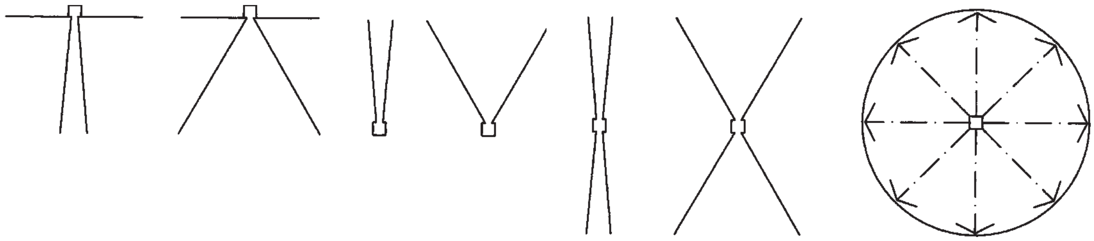


Figure 3.1 The seven directions and distributions of light.

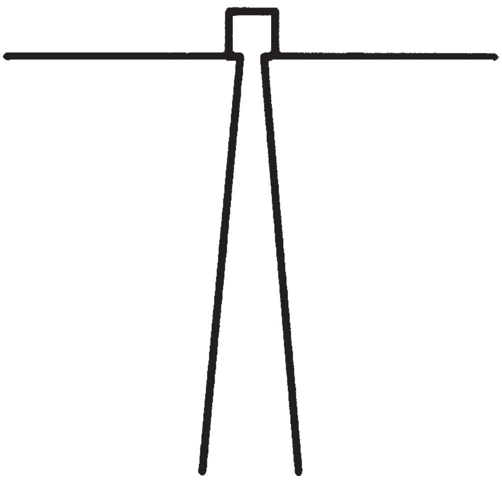


Figure 3.2 Concentrated downward (direct) distribution.

Figure 3.3 An example of concentrated downward distribution.

120°—offer a more practical light distribution for many purposes. A luminaire with a 100° beam-spread, emitting most of its light below a *cutoff* angle of 40° from horizontal, is offered by most well-designed *downlights*. This greater percentage of light at higher angles increases incident light on vertical surfaces, *models* faces, and reduces the concentration of brightness within the space. Diffuse downward luminaires yield a low-contrast setting (figure 3.5).

A *concentrated upward* (*indirect*) distribution directs light toward the ceiling (figure 3.6). With light directed upward and the downward component removed, the ceiling becomes visually prominent. It also becomes a *secondary light source* because of its reflective properties.

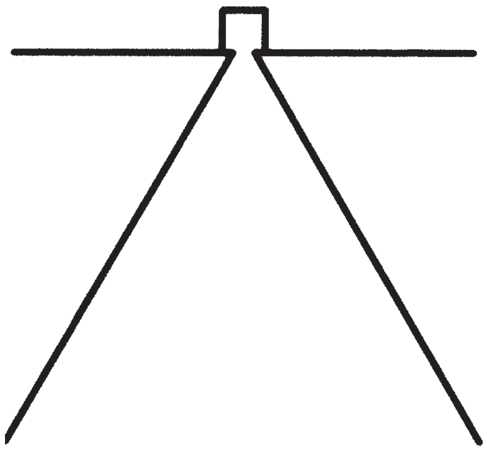


Figure 3.4 Diffuse downward (direct) distribution.

Figure 3.5 An example of diffuse downward distribution.

When mounted in close proximity to the surface being lighted, concentrated upward beams create isolated areas of high luminance. The nonuniformity of concentrated upward distribution reduces the strong contrast that results from a concentrated downward system by adding visual interest through brightness variation (figure 3.7).

If this is the main source of room illumination in areas with low ceiling heights, the "spots" of high brightness on the ceiling become uncomfortable and cause glare. When placed farther from the surface to be lighted, however, concentrated upward beams produce uniform brightness: each beam covers a wider area and multiple beam patterns overlap. In areas with higher ceiling heights, the concentrated beam has sufficient distance to spread; thus the ceiling is lighted uniformly, reducing brightness and glare (figure 3.8).

A *diffuse upward* (*indirect*) distribution directs light toward the ceiling and the upper side walls (figure 3.9). This technique is used to create uniform ceiling luminance for the prevention of glare in areas with video display terminals (VDTs) and to emphasize structural form or decorative detail on or near the ceiling plane (figure 3.10).

Because each point on the ceiling reflects light in every direction, diffuse upward distribution produces a flat, low-contrast environment: the reflected light reduces contrast and shadow; objects and faces have the washed-out appearance similar to that caused by an overcast day.

Multidirectional diffuse (*general diffuse*) distribution is produced by luminaires that deliver both upward and downward components of light (figure 3.11). These luminaires emit light in several directions at the same time—toward the ceiling and walls as well as toward the floor. The reflected light from the ceiling and the interreflection of light in the space diffuse the downward distribution, reducing shadow and contrast and creating a uniform, high-brightness interior (figure 3.12).

Luminaires that deliver both direct and indirect components of diffuse light, but no side lighting, are called *direct/indirect* (figure 3.13).

Figure 3.6 Concentrated upward (indirect) distribution.

Figure 3.7 An example of concentrated upward distribution.

Figure 3.8 An example of concentrated upward distribution with the light source placed farther from the illuminated surface.

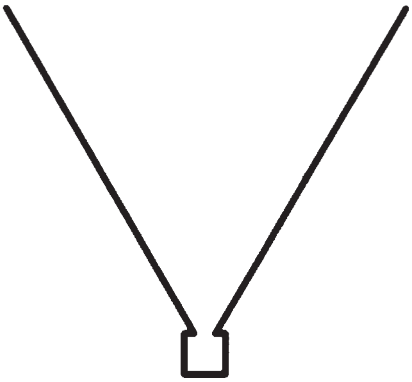


Figure 3.9 Diffuse upward (indirect) distribution.

Figure 3.10 An example of diffuse upward distribution.

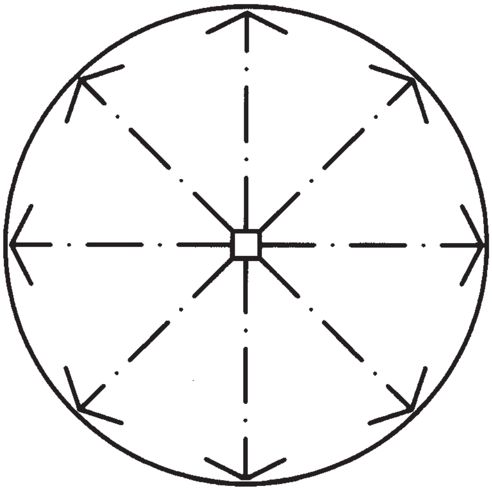


Figure 3.11 Multidirectional diffuse (general diffuse) distribution.

Figure 3.12 An example of multidirectional diffuse distribution.

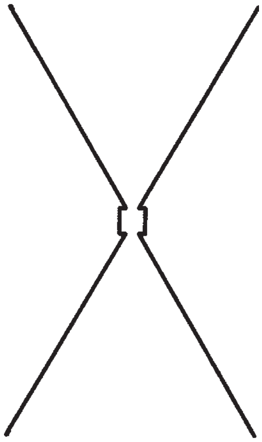


Figure 3.13 Direct/indirect distribution.

Figure 3.14 An example of direct/indirect distribution.

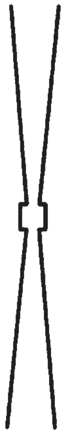


Figure 3.15 Multidirectional concentrated (semidirect or semi-indirect) distribution.

Figure 3.16 An example of multidirectional concentrated distribution.

They provide efficient use of light on work surfaces while relieving contrast by reflecting light from the ceiling plane (figure 3.14).

Multidirectional distribution created with concentrated beam-spreads is called *multidirectional concentrated* (figure 3.15). It is also called *semidirect* if 60% to 90% of the *lumens* (light emanating from the luminaire) are directed downward, and *semi-indirect* if 60% to 90% of the lumens are directed upward.

A higher contrast, nonuniform brightness condition is produced with concentrated distributions present in both the upward and downward components. The upward component reduces excessive contrast in a space; however, the nonuniform light reflected from wall or ceiling surfaces is insufficient to "wash out" all shadow and contrast. This lack of diffusion yields moderate contrast (figure 3.16).

Vertical Surface Illumination

Wall lighting is sometimes a substitute for indirect ceiling lighting: it lightens shadow and reduces excessive contrast. It works especially well when the walls are high in relation to the size of the room. Another substitute is direct downlights in combination with a light-colored floor: the floor reflects light back to the ceiling as though indirect lighting were being used. The floor must be kept clean for this technique to be successful.

The ideal lighting arrangement is often a combination of direct and indirect light, where the direct light takes the place of the sun, casting shadows and modeling shapes, and the indirect light softens the shadows, acting as a blue sky or a photographer's fill light. Direct/indirect lighting designs are produced either with separate systems for downward and upward light or with one system that provides both downward and upward distribution.

SURFACE FINISHES AND REFLECTANCES

What is perceived as brightness is not the incident light on a surface, but the light that is *reflected* from that surface toward the eyes. Brightness results from the intensity of light that initially strikes a surface *and* the reflecting or transmitting properties of that surface.

Whether it is of high or low intensity, some amount of incident light from luminaires or from interreflection falls on all room surfaces. The relative size of these surfaces and the intensity of light reflected from them determine their visual prominence in an interior composition.

Reflected light is usually diffuse and multidirectional, causing interreflection between all surfaces and objects. This interreflection fills in shadows, reduces contrast, and yields more uniform brightness.

The overall brightness results from the distribution of reflected light, which, in turn, depends on the reflectance properties of the surfaces in the space. Dark-colored, low-reflectance finishes absorb much of the light that strikes them, reflecting only a small amount toward the eye. This gives an impression of a dark, high-contrast space regardless of the amount of illuminance (figures 3.17 and 3.18).

Light-colored and high-reflectance finishes reflect much more of the incident light, contributing to a higher brightness and a greater diffusion of light (figures 3.19 and 3.20). This interreflection is independent of the initial distribution of light, whether that distribution is concentrated or diffuse.

The choice of surface finishes augments or negates the initial distribution of light from luminaires. This influence of reflected light must be accounted for: understanding the relationship between lighting equipment and room surfaces is critical to successful lighting design.

Secondary Light Sources

Any object or surface that reflects or transmits light becomes a secondary light source. The moon is an example: it is incapable of producing light. The moonlight we see is produced by a primary source—the sun—which is reflected by the moon's surface.

Similarly, a lighted wall or ceiling becomes a secondary light source that illuminates a room through reflection. The result is then dependent on the reflected light from the lighted surface, rather than on the initial distribution of light from the luminaires (see color plate 5).

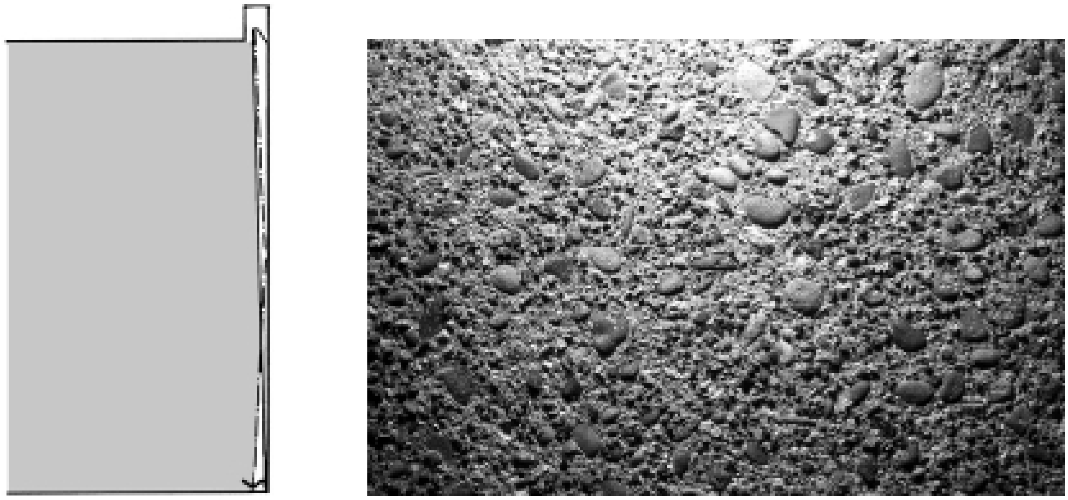
THREE-DIMENSIONAL FORM

In addition to altering our perception of space, the direction and distribution of light affect the perception of surfaces and objects in a room.

All three-dimensional form is seen as a pattern of brightness contrasts, often con-


Figures 3.17 and 3.18 If all the room surfaces are dark, there is little interreflection; contrast is high.


Figures 3.19 and 3.20 If all of the room surfaces are light-colored, interreflections will fill in shadows and reduce contrast.

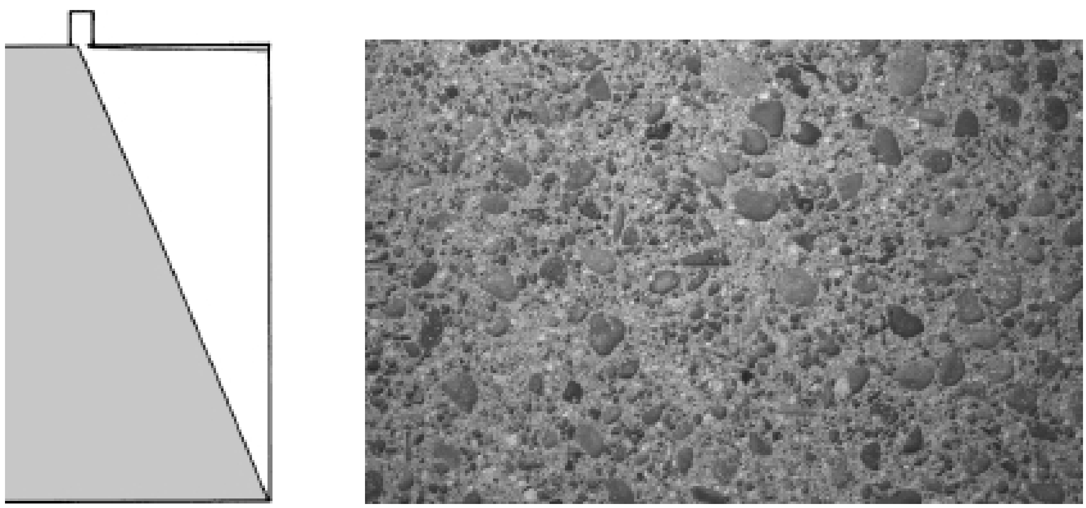


Figures 3.21 and 3.22 Grazing illumination.

sisting of highlights and shadows. A change in this pattern, caused by a change in the direction and distribution of light, alters visual impressions of form and surface.

Lighting alters perception of texture. *Grazing light*, from luminaires located close to a surface being lighted, strengthens highlights and shadows. It enhances the perception of depth by emphasizing the natural textures and sculptural relief of the surface. Grazing light is also used for inspection to detect surface blemishes and errors in workmanship (figures 3.21 and 3.22).

Grazing light is appropriate for lighting heavily textured surfaces such as rough plaster, masonry, or concrete. It is disastrous for "flat" walls of smooth plaster or gypsum board, however, because such walls are not



Figures 3.23 and 3.24 Diffuse wash light.

Figure 3.25 Sculpture lighted with concentrated direct lighting from below.

Figure 3.26 Sculpture lighted with diffuse lighting from above.

truly flat: minor surface imperfections such as trowel marks, tape, and nail-head depressions are magnified by the shadows that result from grazing light.

Conversely, diffuse *wash light* reduces the likelihood that surface flaws will be noticed and strengthens an impression of surface smoothness. This is more suitable for a gypsum board wall or an acoustical tile ceiling. Diffuse wash light from the front is particularly successful at reducing or removing shadows and small variations in brightness (figures 3.23 and 3.24).

Concentrated direct lighting on objects produces drama and emotional excitement. Yet the same sharp shadows that contribute to the dramatic impact also reduce visibility of detail. This diminishes the ability to study and appreciate all aspects of the object accurately (figure 3.25).

A diffuse lighting distribution, on the other hand, illuminates the entire object, reducing shadows and facilitating study of workmanship and detail. Although it is often desirable, this kind of lighting sacrifices the dramatic impact and visual excitement (figure 3.26).

Sharp highlights and dark shadows create a dramatic setting and strengthen impressions of texture and form; however, they are distracting in a working environment. Some shadows on a work surface are mildly irritating, such as those cast by a hand or pencil while one is writing under a concentrated light source.

Other shadows are extremely distracting and even hazardous, such as those on an assembly line. During a period of sustained visual activity, the extreme concentration and constant reädaptation required by workers in high contrast settings result in visual fatigue, errors, and accidents.

Sometimes highlight and shadow are desirable in a work environment. Just as the highlights and shadows of a sunny day are emotionally stimulating, carefully placed highlights and shadows in an interior provide visual relief and interest. Office and factory workers benefit from the stimulation and variation provided by greater brightness con-

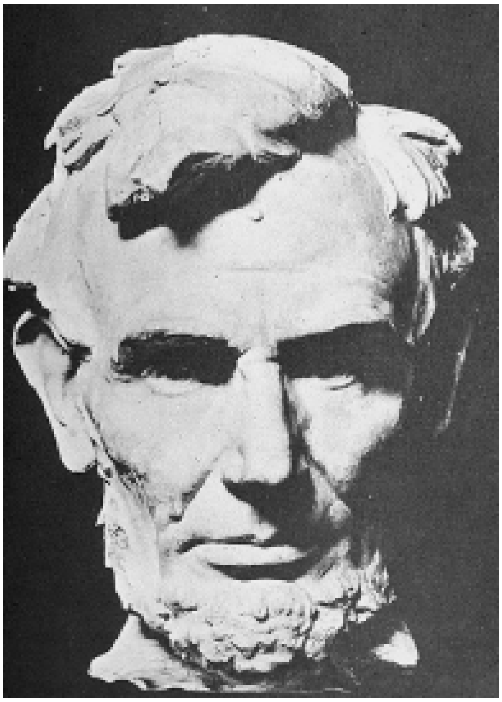


Figure 3.27 Bust of Lincoln lighted from above.

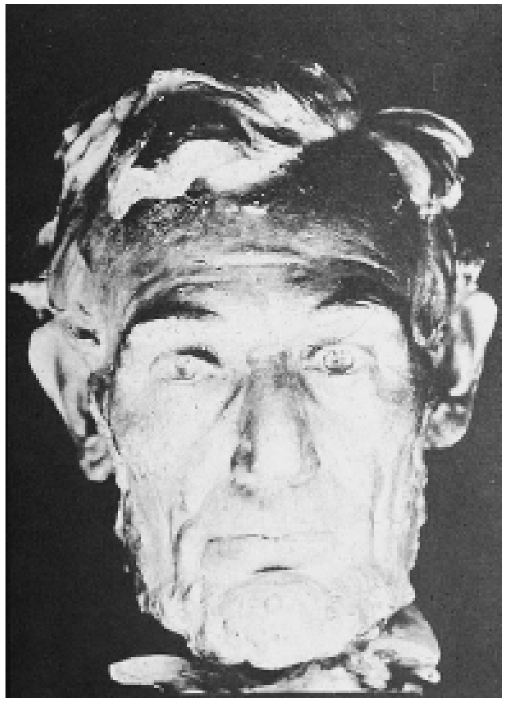


Figure 3.28 Bust of Lincoln lighted from below.

trast in corridors, washrooms, lunchrooms, lounges, and other meeting places. On most *work* surfaces, however, diffuse light distribution is desirable to minimize highlights and shadows.

Experience and memory also influence our perception of objects. Through the course of time, people have come to expect midday sunlight to emanate from a concentrated source overhead, at an angle less than 45° from nadir (straight down), and skylight to be a diffuse, multidirectional source.

When a lighting system alters the expected direction of light, it changes the normal relationship between highlights and shadows. An unnatural impression results, inducing mystery or anxiety (figures 3.27 and 3.28).

In practice, objects being exhibited or photographed are often lighted from two sides to reduce excessive shadows. One side has a concentrated beam-spread to enhance drama and function as the sun's directional rays; the other side receives diffuse illumination to soften shadows and replicate the sky's diffusing quality. The background may be lighted separately to distinguish the object from its surround and to add visual depth.

GLARE AND SPARKLE

Excessive contrast or luminance is distracting and annoying. This negative side of brightness is called *glare*. In the extreme, glare cripples vision by reducing or destroying the ability to see accurately.

Glare is often misunderstood as "too much light." In fact, it is light coming from the wrong direction, the result of an extreme luminance within the normal field of view. The difference between the high and low beams

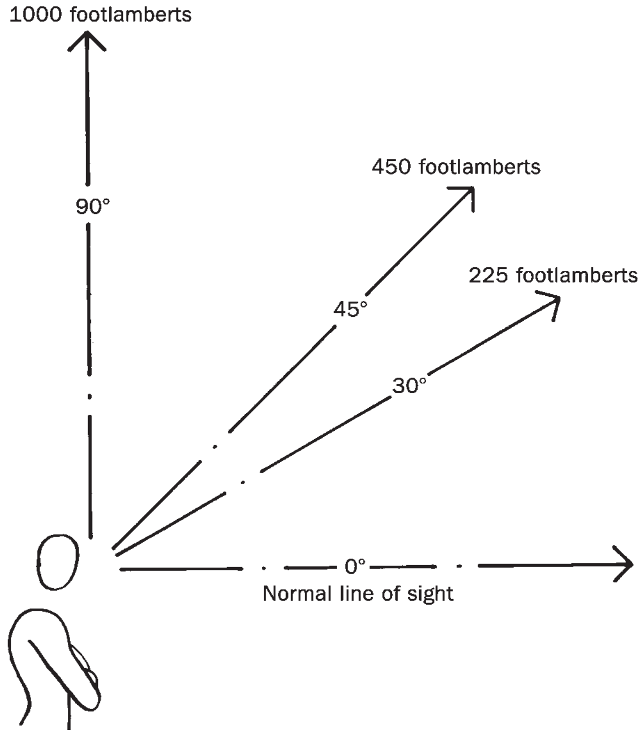


Figure 3.29 Acceptable luminance values decrease as the source approaches the center of the visual field.

of automobile headlights at night demonstrates that glare for the approaching driver is a function of direction as well as intensity. It also demonstrates that glare may be present in an environment with little light.

Glare is also a function of luminance area. Although a small area of luminance is tolerable, a larger area of the same intensity becomes uncomfortable. It is desirable to reduce luminance intensities as the area of luminance becomes more dominant in the field of view.

In addition, glare is a function of location. Within limits, the human eyebrow conceals glare from overhead luminaires, but not from poorly shielded, wall-mounted luminaires or high-luminance wall surfaces, as these elements are directly in the field of view (figure 3.29).

Direct Glare

The late afternoon sun and an unshielded electric light source are examples of the distracting influence of direct glare in the environment. *Direct glare* is caused by the lighting system; it is defined as excessive light misdirected toward the eye.

Usually, the uncontrolled luminance of an exposed light source produces glare. For this reason, bare *lamps* (the technical word for light bulb) are rarely used in architectural applications (figure 3.30).

When direct glare occurs in the normal field of view, three main control techniques are available. One is to limit the amount of light emitted in the direction of the eye (figure 3.31). Shielding devices such as the hand, used instinctively, and sun visors improve visibility and restore visual comfort in this way.

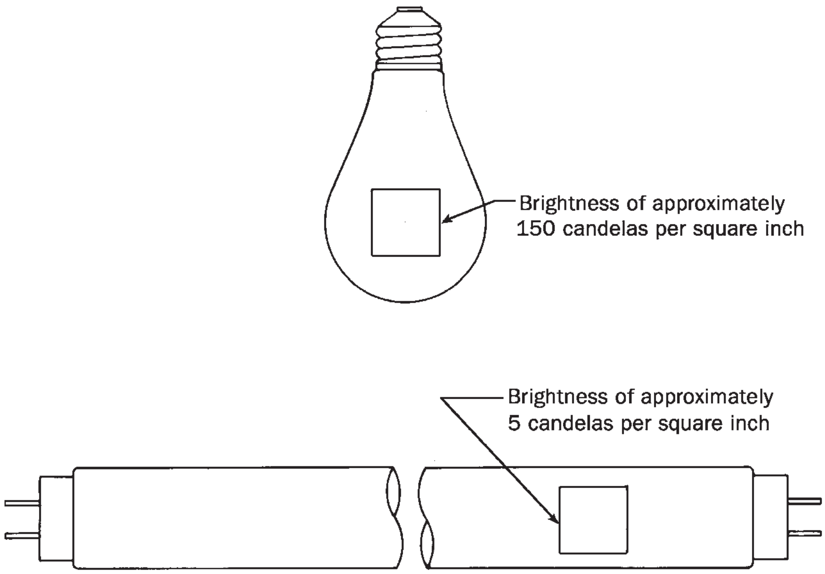


Figure 3.30 Unshielded lamp luminance for equivalent light output.

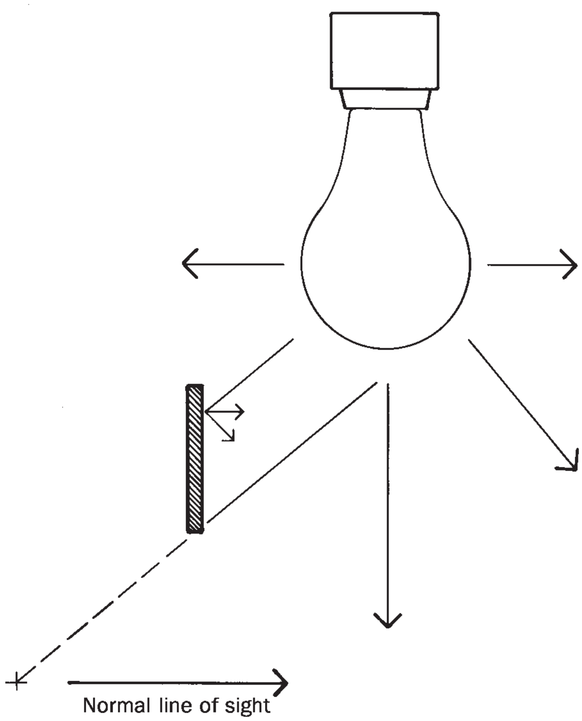


Figure 3.31 Limiting the amount of light emitted toward the eye.

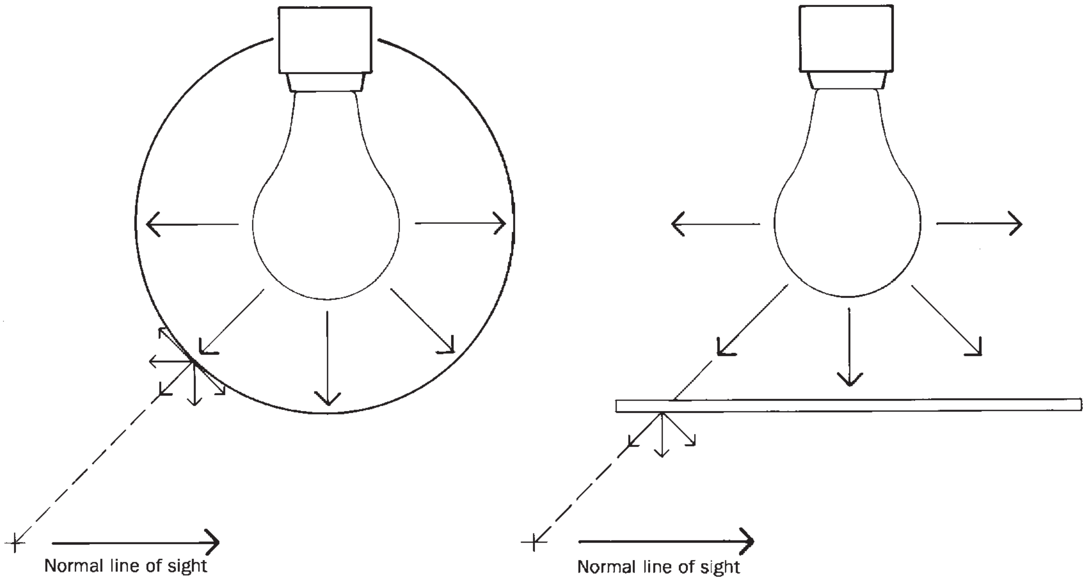


Figure 3.32 Increasing the area from which light is emitted.

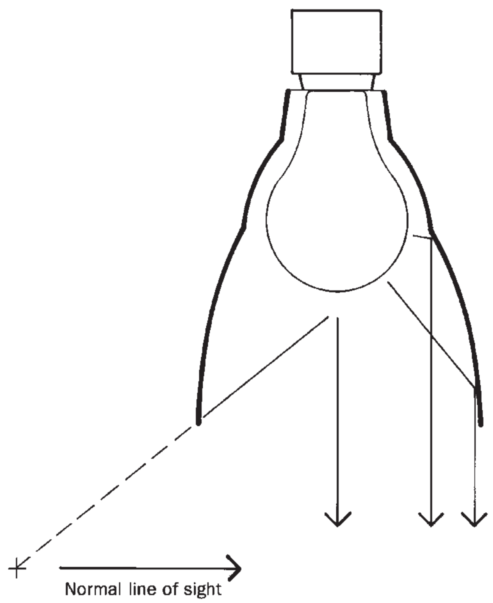


Figure 3.33 Change in the direction of the beam to control direct glare.

The second is to increase the area from which light is emitted (figure 3.32). A white glass globe and diffusing panels of white glass or plastic are examples.

The automobile headlights redirected below the line of sight demonstrates the third technique whereby directional control and change in the direction of the beam (figure 3.33) aid visual comfort. This third method is more efficient; it uses accurate control devices to redirect light in the desired direction. Typical devices are reflectors and refracting lenses that limit the distribution of stray light emitted toward the eye.

Visual comfort results from the reduction of glare and distracting luminance in the field of view. Excessive luminance is physiologically disconcerting and reduces the ability to see detail accurately. The quality and comfort of vision depend upon the avoidance of distracting or disabling luminances.

Visual Comfort Probability (VCP)

A *visual comfort probability (VCP)* rating is defined as the percentage of people who, if seated in the least desirable location in an office work space, will find a lighting installation comfortable. VCP depends on the size and shape of the room, the reflectances of room surfaces, and the location and light distribution of the luminaires.

A VCP of 70 or more is recommended for general office use, and 80 or more for office areas using video display terminals (VDTs). Originally tested and validated using lensed fluorescent direct luminaires, VCP is applicable only for direct lighting systems.

Reflected Glare

Visual comfort is achieved by limiting not only direct glare but also reflected glare. *Reflected glare* is excessive uncontrolled luminance reflected from objects or surfaces in the field of view. This includes the reflected luminance from interior surfaces as well as the luminance of the lighting system.

Specular surfaces have reflecting properties similar to those of a mirror. The luminance reflected is the mirrored image of the light source, or of another lighted surface within the reflected field of view.

These properties make specular surfaces useful as reflectors for light control in luminaires, but polished or specular interior surfaces such as desks, countertops, floors, walls, and ceilings introduce problems of reflected glare. *Diffuse surfaces* prevent highlights and are uniformly bright from all angles of view.

Reflected images on glass and other transparent materials form a visual barrier. At night, large areas of glass may become black mirrors. If surfaces viewed through the transparent material are higher in luminance than the reflected images, a sense of transparency is achieved.

Most work surfaces reflect light both diffusely and specularly. Diffuse reflectance is dependent on the quantity of illuminance on the surface. Specular reflectance is dependent on the luminance of the source: the reflected image of the lamp or luminaire. This reflected image causes a veiling image on the work surface that obscures surface detail.

In the visual task area, remove glossy surfaces wherever possible. A glass-covered or highly polished desk top is quite specular; reflected images become distracting. Matte (low-gloss) finishes should always be used for work surfaces.

It is helpful to think of the work surface as a mirror when orienting task luminaires (figure 3.34). Proper luminaire location reduces reflected glare from the task (figure 3.35). When luminaires are located on either side of the desk, shadows cast by the luminaires are filled in and light is reflected away from the worker's eyes (figure 3.36).

Video Display Terminals (VDTs)

VDTs are glossy *vertical* work surfaces. Screen reflections are caused by variations in luminance being "seen" by the screen surface and reflected into the worker's eyes. Screens that are convex and inclined upward, in particular, reflect into the eyes large areas of ceiling, walls, windows, and the surrounding space.

Positioning the screen, adjusting its angle, low-reflectance screens, blinds on windows, and dark clothing for workers are techniques that relieve many reflection problems. Reflections caused by the lighting system can be controlled with properly designed, deep-cell parabolic louvers to prevent lamp images from appearing on the VDT screen.

In addition to reflections on the screen surface, which make viewing the screen images difficult, two additional lighting problems that cause concern for VDT users are: (1) proper lighting for the non-VDT tasks the

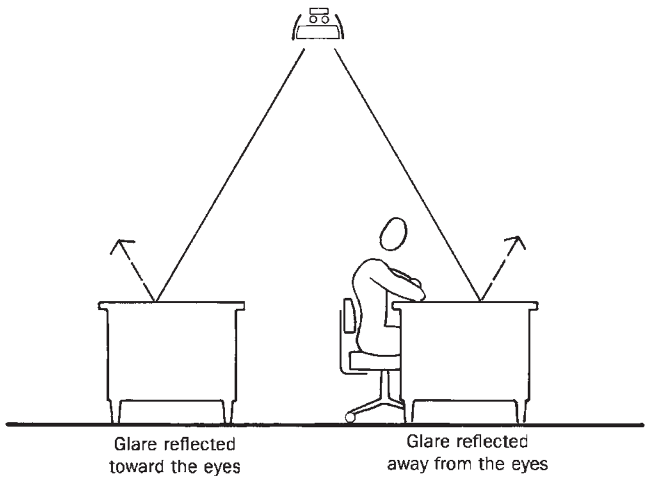


Figure 3.34

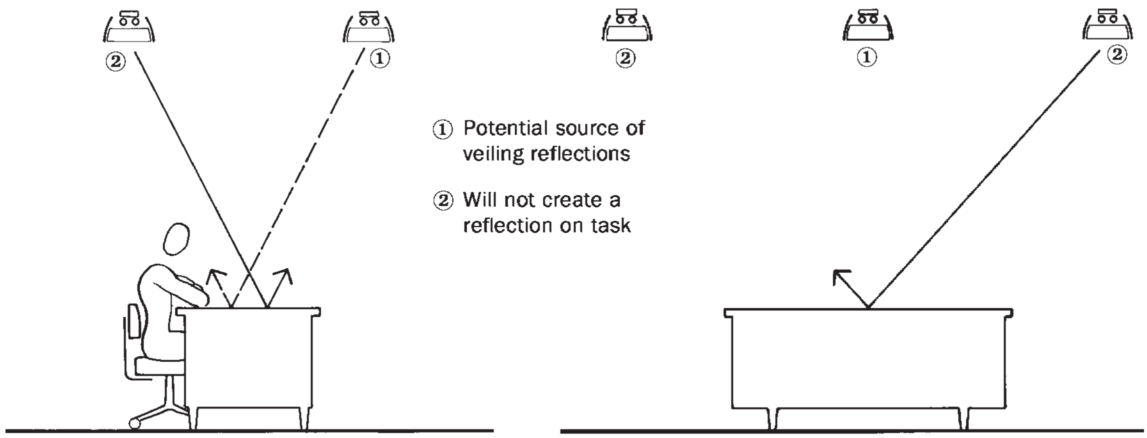


Figure 3.35

worker must also perform, and (2) lighting of the area in the worker's field of view.

Sometimes the ambient room illuminance in VDT areas is set low in the belief that this improves screen visibility. The opposite is true. While low quantities of ambient light reduce screen reflections, the room appears visually gloomy; there will also be areas of high contrast between the bright screen and the dark surround. Furthermore, low ambient illuminance is unstimulating, especially when contact with the outdoors via windows is missing.

Indirect uplighting systems are sometimes used to avoid luminaire reflections in the screen. The ceiling must be high enough to allow pendant- or floor-mounted luminaires to distribute light evenly (see figure 13.21) or

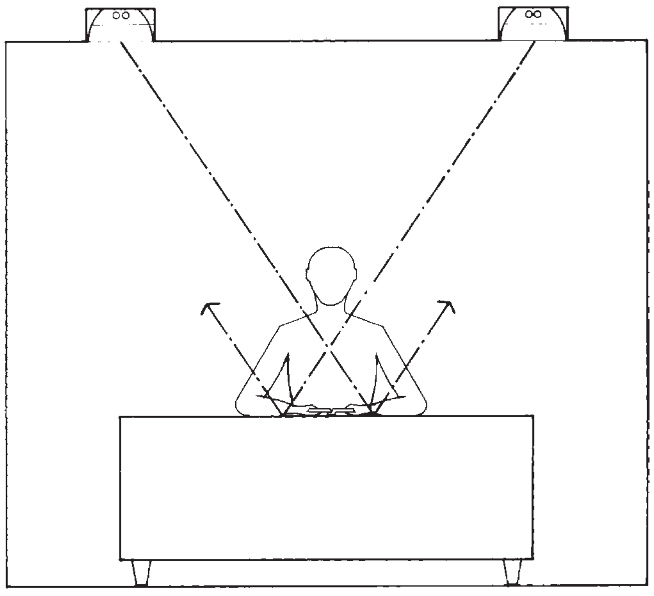


Figure 3.36 Proper desk lighting.

excessive contrast is created in a different way. Even when uniform ceiling luminance is achieved, the diffuse reflected light may have a "washing out" effect that reduces the visibility of the screen. Moreover, because all of the light in the space is diffuse, indirect systems also create a bland interior.

It is the *variation* in room luminance that is extremely critical, however. All surfaces and objects reflected by the VDT screen into the worker's normal line of sight—especially room surface finishes such as system divider panels, vertical surfaces of filing cabinets, and the ceiling plane—must be of more or less equal luminance if distracting images are to be prevented.

Many high-quality VDTs are now furnished with integral low-reflectance screens; newer, flat-screen monitors have liquid crystal displays (LCDs), which reflect very little light from all directions except perpendicular to the screen. In time, VDTs may cease to be a lighting challenge.

Sparkle

The principal difference between glare and sparkle is the relationship between the area and magnitude of luminance in the field of view. Large areas of luminance are distracting and disconcerting; relatively small areas of similar or higher intensity are points of sparkle and highlight that contribute to emotional excitement and visual interest.

• **Direct sparkle**. Examples include Christmas tree lights; small, exposed, clear filament lamps; and perforated shielding materials (see color plate 6).

• **Reflected sparkle**. Examples include textured metal and pebbled surface finishes (see color plate 7).

• **Transmitted sparkle**. Examples include crystal chandeliers and sandblasted- or etched-glass (frosted) *diffusers* around clear filament lamps. Clear filament lamps combined with crystal glass, particularly when that glass is faceted, introduce subtle color highlights via the dispersion of "white" light into the rainbow of colors that comprise it (see color plate 8).

The presence of sparkle, highlight, and shadows constitutes the chief visual attributes that make a sunny day interesting and stimulating; their absence makes a cloudy, overcast day flat and dull. The emotional stimulation provided by carefully controlled sparkle, highlight, and shadows is equally significant in interiors.

4 Color

Color is not a physical property of the things we see—it is the consequence of light waves bouncing off or passing through various objects.

The color of an object or surface is determined by its reflected or transmitted light. Color is not a physical property of the things we see—it is the consequence of light waves bouncing off or passing through various objects. What is perceived as color is the result of materials reflecting or transmitting energy in particular regions of the visible spectrum.

Green glass transmits the green portion of the spectrum, absorbing almost all of the other regions; yellow paint reflects the yellow portion, absorbing almost all other wavelengths (figure 4.1). White or neutral gray materials reflect all wavelengths in approximately equal amounts.

Pure spectral colors are specified by their wavelength, which is usually expressed in nanometers. A nanometer (nm) is one billionth of a meter or about thirty-nine billionths of an inch.

The reflectance chart (color plate 9) shows that butter absorbs blue light and reflects a high percentage of all other colors; these other colors combine to produce what we call yellow. Green lettuce reflects light with wavelengths primarily in the 500–600-nm region and absorbs all of the energy at other wavelengths. A tomato is red only because it reflects visible energy at 610 nm while absorbing almost all of the other wavelengths.

A light source that emits radiant energy comparatively balanced in all visible wavelengths appears “white” in color. Passing a narrow beam of this white light through a prism separates and spreads the individual wavelengths, allowing the eye to distinguish among them. The resulting visual phenomenon is called a *color spectrum* (color plate 2).

“White” light sources emit energy at all or almost all visible wavelengths, but not always in an ideal proportion. Almost all sources are deficient at some wavelengths yet still appear to be white. This deficiency influences the perception of colors; the effect is known as *color rendition*. It causes the graying of some colors while enhancing the vividness of others.

To provide accurate color perception, a light source must emit those wavelengths that a material reflects. Lighting a tomato’s surface with a white light source makes the

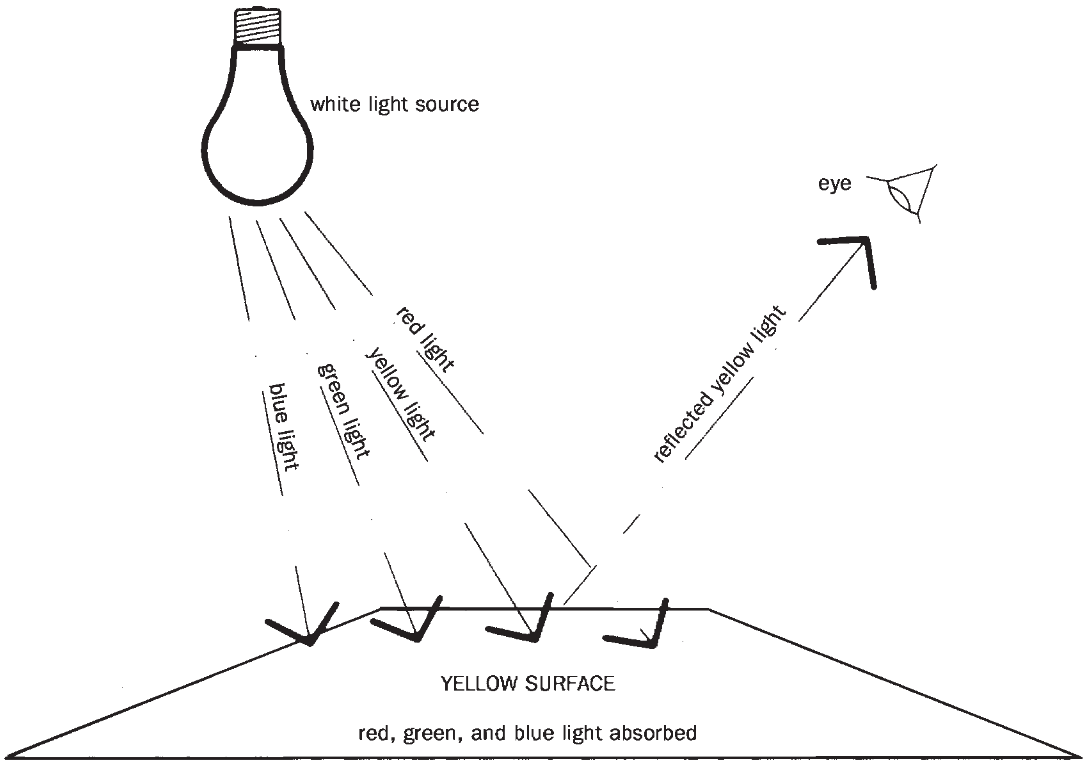


Figure 4.1 To provide accurate color rendition, the light source must emit the wavelengths that the object reflects.

surface appear red, because only red wavelengths of light are reflected toward the eye. All other wavelengths are absorbed.

If the tomato is lighted with a green source, however, it will appear dark gray because no red energy is available to be reflected. The eye can see only the colors of a surface that are present in the source of illumination (color plate 10).

Because the proportion of colors in "white" light varies, what we call white light is a broad category. Within this category, the most common variations are described as "warm" or "cool." A warm white light emphasizes the long (high nm) end of the spectrum, with hues of yellow through orange to red. Warm light sources that emphasize these hues include the sun and *incandescent, tungsten-halogen,* and *high-pressure sodium* lamps. Conversely, a cool white light source emphasizes the short (low nm) end of the spectrum, with hues of blue through green to yellow. Cool light sources that emphasize these hues include north skylight and many *fluorescent* and *metal halide* lamps.

Spectral distribution charts, available from lamp manufacturers, express the relative color composition of light sources (color plates 13–17 and 19–31). Because these charts are of limited practical value in predicting how colors will appear, simplified systems of color notation and color rendition have been developed.

COLOR TEMPERATURE

Color temperature describes how a lamp appears when lighted. Color temperature is measured in kelvin (K), a scale that starts at absolute zero (–273°C).

At room temperature, an object such as a bar of steel does not emit light, but if it is heated to a certain point it glows dull red. Instead of a bar of steel, physicists use an imaginary object called a *blackbody radiator*. Similar to a steel bar, the blackbody radiator emits red light when heated to 800 K; a warm, yellowish “white” at 2800 K; a daylight-like white at 5000 K; a bluish, daylight white at 8000 K; and a brilliant blue at 60,000 K. The theoretical blackbody is necessary because the bar of steel would melt at these higher temperatures.

Color temperature is not a measure of the surface temperature of an actual lamp or any of its components. Color temperature refers to the absolute temperature of the laboratory blackbody radiator when its visible radiation matches the color of the light source.

Incandescent lamps closely resemble blackbody radiators in that they emit a continuous spectrum of all of the visible colors of light (color plate 13). Consequently, the incandescent spectrum is accurately specified by color temperature in kelvin. Fluorescent and *high-intensity discharge* (HID) lamps produce a discontinuous spectrum with blank areas punctuated by bands at specific frequencies (color plates 14–17 and 19–31). These bands combine to give the impression of “white” light; fluorescent and HID lamp color appearance is specified by its *apparent* or *correlated color temperature* (CCT).

Incandescent lamps used in architectural lighting have color temperatures in the 2600 K to 3100 K range; fluorescent lamps are available with apparent color temperatures from 2700 K to 7500 K; north skylight is arbitrarily called 10,400 K.

Unfortunately, the apparent color temperature of discontinuous spectrum light sources fails to provide information about its spectral energy distribution. For example, warm white and RE-930 fluorescent lamps have the same apparent color temperature, yet their spectral distribution curves and their color rendition of objects and materials are vastly different. This same limitation applies when using color temperature notations for high-intensity discharge sources, including *mercury vapor*, metal halide, and high-pressure sodium lamps.

COLOR RENDERING

To remedy this limitation, *color rendering* expresses how colors appear under a given light source. For example, a shade of red will be rendered lighter or darker, more crimson or more orange, depending on the spectral-distribution properties of the light falling on it.

The most accepted method to determine the color-rendering ability of a light source is a rating system called the *Color Rendering Index* (CRI).

The CRI first establishes the real or apparent color temperature of a given light source. Then, it establishes a comparison between the color rendition of the given light source and of a reference light source. If the color temperature of a given source is 5000 K or less, the reference source is the blackbody radiator at the nearest color temperature. If the given color temperature is above 5000 K, the reference source is the nearest simulated daylight source.

The comparison is expressed as an R_a factor, on a scale of 1 to 100, which indicates how closely the given light source matches the color-rendering ability of the reference light source. Since the reference for CRI changes with color temperature, the

CRIs of different lamps are valid only if they have similar correlated color temperatures. Therefore, it is inappropriate to compare two light sources unless their color temperature is similar—within 100 K to 300 K.

For example, a 3000 K RE-70 fluorescent lamp and a 6500 K "daylight" fluorescent lamp render objects differently, despite the fact that they both have a CRI of 75. This occurs because the CRI for the 3000 K lamp was compared to a blackbody radiator and the CRI for the 6500 K lamp was based on comparison to actual daylight.

R_a is an average of the color rendering ability of eight test colors; better performance at some wavelengths is concealed when averaged with poorer performance at other wavelengths. As a consequence, two lamps that have the same color temperature and CRI may have different spectral distributions and may render colored materials differently.

Some typical CRIs appear in table 1 in the appendix.

The color properties of the light source significantly alter the appearance of people. Because incandescent sources are rich in red wavelengths, they complement and flatter complexions, imparting a healthy, ruddy, or tanned quality to the skin. Cool fluorescent and HID sources that emphasize the yellow or blue range produce a sallow or pale appearance.

SUBJECTIVE IMPRESSIONS

The color of light has a profound effect on subjective impressions of the environment. The Amenity Curve indicates that warmer light is desirable for low luminance values (figure 4.2). It also shows that a room uniformly lighted to 20 footcandles (fc) will be unpleasant with either kerosene lamps (about 2000 K) or lamps that simulate daylight (about 5000 K).

With the warm-toned kerosene source, the quantity will seem too high and the space too greatly lighted. With the simulated daylight source, the same quantity of light will seem dark and dingy. Both warm fluorescent (2700 K or 3000 K) and standard incandescent lamps (2600 K to 3100 K) fall within the acceptable range on the chart.

In addition, a warm atmosphere suggests friendliness or coziness. A cool atmosphere implies efficiency and neatness. Flynn evaluated subjective responses to colors of white light that are produced by electric light sources in interior spaces at intermediate illuminance values.

Flynn's subjects categorized their impressions of visually warm versus visually cool space as follows: cool colors (4100 K) stimulate impressions of visual clarity; warm colors (3000 K) reinforce impressions of pleasantness, particularly when a feeling of relaxation is desirable.

Flynn found that diffuse light plus warm (orange-red) hues intensify impressions of tension and anxiety. Diffuse light plus cool (violet-blue) hues reinforce impressions of somberness; at low luminance values, they create an impression of gloom.

He also found that patterns of sparkle plus saturated warm (orange-red) hues strengthen impressions of playfulness and merriment; this is particularly strong with random patterns of light and color. Patterns of sparkle plus saturated cool (violet-blue) hues reinforce impressions of enchantment; this is particularly strong with rhythmic or regimented patterns of light and color.

SURFACE FINISHES AND COLOR OF LIGHT

To reiterate: light does not have color, and objects do not have color. Color resides in the eye/brain system.

The relationship between the spectral distribution of light and the colors of fabrics, walls, and other elements in the interior is, therefore, pivotal. Some objects appear to

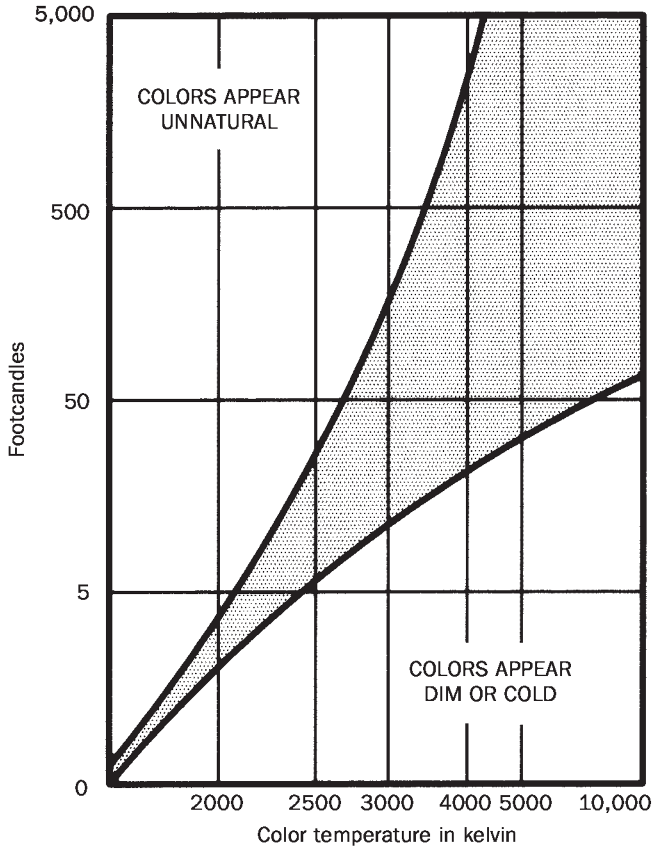


Figure 4.2 Amenity Curve, based on a pilot study by A. A. Kruithof, 1941.

be the same color under a certain light source although they are different in spectral composition. If the light source is changed, however, the object color differences become apparent (color plate 11).

It is advisable to appraise, match, and specify colored materials using light sources identical in color to those that will be used in the completed installation. When the lighting system that will be installed is unknown, two light sources of different spectral character may be used to examine the samples: one of the sources should be predominantly blue in spectral distribution, such as a daylight fluorescent lamp, and the other predominantly red, such as an incandescent lamp.

Incandescent Sources

Incandescent lamps emit energy in a smooth curve beginning with a small amount of deep-blue radiation in the near ultraviolet range and increasing into the deep-red portion of the spectrum (color plate 13). The color of incandescent light is warm in tone, with most of the energy concentrated in the red and yellow range. Although this “white” light is deficient in blue and green, and tends to gray these colors, it complements the appearance of warm colors and human faces.

Incandescent lamps enjoy one slight advantage over other lamps in color rendering—not because they render colors more naturally, but because more than a century of use has established them as a norm. Incandescent lamps also produce light as a by-product of heat, similar to other sources of light that have been familiar for thousands of years: the sun, open fire, candles, oil lamps, and gas lamps. All of these give warm-colored light and all are *point* sources.

Good color rendition is usually interpreted to mean the familiar appearance of familiar objects: things assume familiar colors by frequently being seen under certain kinds of light sources, such as incandescent lamps or daylight.

Tungsten-halogen lamps (3000 K) have more blue and less red energy than standard incandescent lamps; they appear whiter than the slightly yellowish standard incandescent lamps (2700 K). All incandescent and tungsten-halogen lamps are assigned a CRI of 100.

Fluorescent Sources

Fluorescent lamps produce a discontinuous spectrum: peaks of energy at specific wavelengths. Variations in the composition of the *phosphors* that coat the inside of the lamp produce differences in the color of emitted light. Three principal color temperatures are available with fluorescent lamps: (1) warm (3000 K) lamps are compatible with incandescent lamps, (2) cool (4100 K) lamps are compatible with daylight, and (3) 3500 K lamps are compatible with both.

Fluorescent lamps also fall into three groups with regard to *efficacy* and color rendition: standard, deluxe, and rare-earth. Standard white lamps—both cool and warm kinds—produce high efficacy and poor color rendition (color plates 14 and 16). Warm white fluorescent lamps have CRIs of 52 to 53; cool white fluorescent lamps have CRIs of 60 to 62.

Deluxe white lamps produce improved color rendering with an approximately 25 percent sacrifice in lighting efficacy. The reduction in light quantity is often imperceptible, however, because of the vivid and accurate colors that improve contrast and portray tones that are grayed with standard lamps (color plates 15 and 17). Deluxe fluorescent lamps have CRIs between 84 and 89.

For both high color rendering and high luminous efficacy, rare-earth lamps are used. Three kinds of rare-earth (RE) lamps are available: triphosphor RE-70, triphosphor RE-80, and quad-phosphor RE-90.

Triphosphor rare-earth lamps produce light in accordance with the theory that the human eye reacts to three *prime colors*—blue-violet, pure green, and orange-red (color plate 18). When these three prime (not primary) colors are combined in a triphosphor lamp, only those wavelengths are emitted; the brain fills in the remainder of the spectrum. This yields more colorful interiors because the three narrow-emission, prime-color phosphors compress all hues into the eye's color response system, increasing color contrast (color plates 19, 20, and 21).

Because the eye/brain system can be fully stimulated with these three monochromatic wavelengths, all pigment colors can be rendered by adjusting the relative intensities of the three prime-color phosphors. The key is to choose the components that maximize the visual system responses. For maximum effect, the three wavelengths must correspond to the peak spectral sensitivities of human vision, which are near 450 nm, 530 nm, and 610 nm.

RE-70 lamps use a coat of conventional phosphors and a thin coat of narrow-emission, rare-earth phosphors, producing CRIs of 70 to 78. *RE-80* lamps use a thick coat of the narrow-emission, rare-earth phosphors, producing CRIs of 80 to 86.

Quad-phosphor *RE-90* lamps do not use the narrow-emission phosphors; they contain four wider-emission phosphors that produce CRIs of 95 at 3000 K and 98 at 5000 K (color plates 22 and 23). RE-90 rare-earth lamps with CRIs of 95 to 98 are the highest color-rendering fluorescent lamps available.

High-Intensity Discharge (HID) Sources

As with fluorescent lamps, high-intensity discharge (HID) lamps produce a discontinuous spectrum. The different metals in the arc of the various HID sources yield different color-rendering abilities.

If you were to throw salt on a barbecue, the sodium chloride would make the flames appear yellow. Similarly, the sodium in high-pressure sodium lamps makes their color appear yellow. If you were to throw mercury on a barbecue, although this is not recommended because it would cause mercury poisoning, the mercury would make the flames appear blue. Similarly, the mercury in mercury vapor lamps makes their color appear blue.

High-pressure sodium lamps produce predominantly yellow light at 2100 K, which creates a shift in how we perceive almost all observed colors. Reds, greens, blues, and violets are muted (color plate 24). High-pressure sodium lamps have CRIs of 21 and 22.

By further increasing the gas pressure inside the lamp, *white high-pressure sodium* lamps produce incandescent-like color at 2700 K with good color-rendering properties and a CRI of 85 (color plate 25).

Low-pressure sodium lamps emit all visible energy at 589 nm, which means that they render only materials that reflect light at that wavelength. All other colors appear gray (color plate 26). Low-pressure sodium lamps are assigned a CRI of 0.

The clear mercury vapor lamp produces a cool, “white” light of predominantly blue and green energy. The lack of energy at the warm (red) end of the spectrum results in poor color rendering; people appear ghastly. Clear mercury vapor lamps exhibit particularly poor rendering of red. Rendering of other colors is fair, but blues appear purplish (color plate 27). Clear mercury vapor lamps have CRIs between 15 and 20.

Applying a phosphor coating to the inside surface of a mercury lamp’s outer bulb slightly improves the color-rendering properties, but also reduces its efficacy. The phosphors convert invisible ultraviolet energy into visible light (color plate 28). Phosphor-coated mercury vapor lamps have CRIs of 45 to 50.

Metal halide lamps are similar in construction to mercury vapor lamps, except that various metal halides have been added. These halides add missing wavelengths that improve the mercury lamp’s spectral distribution, yielding a more uniform spectrum and better color rendering, but reds are slightly muted (color plate 29). The addition of phosphor coatings on the inside of the bulb provides diffusion and some additional color improvement (color plate 30). A broad range of color-rendering quality exists in the different metal halide lamps; many experience lamp-to-lamp color inconsistency and color shift over the lamp life. The majority of metal halide lamps have CRIs of 65 to 70.

New *ceramic metal halide* lamps combine the ceramic arc tube technology of high-pressure sodium lamps with existing metal halide chemistry. The ceramic arc tube minimizes color variation between lamps and limits color shift during lamp life.

Because it can withstand higher operating temperatures, color rendering is also improved; ceramic metal halide lamps have CRIs of 81 to 96 (color plate 31). These are the highest color-rendering HID lamps available.

A "best" lamp color is nonexistent, as is "true" color. Each spectral distribution results in different object colors, whether that distribution comes from natural sources, such as sunlight or skylight, or from electric sources, such as incandescent, fluorescent, or HID lamps. The "right" color source for a given application depends upon an evaluation of trade-offs, including directional control, familiarity, color rendition, efficacy, absence of glare, maintenance, and cost.

5

Daylight

The goal of daylight design is to provide visual variety with controlled brightness contrasts.

A principal characteristic of daylight is its variability. The color of daylight changes with the time of day, the cleanliness of the atmosphere, and the interreflection of surrounding objects. The intensity of the sun changes with the time of day, the time of year, and the latitude of the site. The luminance of the sky depends on whether the light is coming from an overcast sky, from a clear sky only, or from a clear sky and direct sunlight.

Daylight has two components: sunlight and skylight. *Sunlight* is the directional beam emitted by the sun; *skylight* is the diffuse reflection of light from particles in the atmosphere.

Direct sunlight is usually an impractical source for interiors unless it is shielded. Just as electric luminaires are designed to reduce glare, direct sunlight entering interior spaces requires careful control. For critical seeing tasks, sunlight often causes excessive luminance differences that result in discomfort and poor visibility. This high contrast in the field of view inhibits the eye's ability to adjust, leading to visual fatigue and disturbing the accommodation needed for clear vision.

Skylight, on the other hand, is a useful source without shielding. Although special building configurations or controls are necessary to make skylight acceptable for horizontal tasks at the workplane or for displaying art, it is used with less control to light noncritical seeing areas such as corridors, stairwells, cafeterias, and seating areas.

People require changing stimuli to remain sensitive and alert. For example, gazing out the window at distant objects provides relief for the muscles of the eye. And the constantly changing nature of daylight satisfies our biological and psychological needs for change—a view of the sky provides information about the time of day, which helps maintaln our biological cycles, and the varying light intensity as a cloud passes in front of the sun provides respite or stimulation, which helps reduce monotony.

The proper introduction of daylight into the interior is the simplest way to provide this change. The goal of daylight design is to provide visual variety with controlled brightness contrasts.

Comfort requires moderate changes. Monotony will cause fatigue, but so will overstimulation. Excessive contrast provides emotional appeal but also impairs visual performance. The sudden appearance of a beam of sunlight on a task will provide momentary change and relief; if it remains it will soon cause visual fatigue and stress.

Daylight and view do not necessarily go together and often are achieved through different building openings. The criteria for producing a view to the exterior are different from the criteria for producing good interior daylight.

The more complex the view and the more frequent the changes, the greater will be our satisfaction. Although large windows are sometimes desirable, people's basic need for a view of the outside can be satisfied with comparatively small openings.

DAYLIGHT DESIGN

Window size and height above the work surface are factors in daylighting design. Of course, as the window becomes larger in size, the amount of daylight increases. But the height of the window is the more significant factor.

The higher the window opening, the deeper the daylight can penetrate into the room, and if it is high enough, it may prevent exterior brightness from causing glare. This high-entry light is softened and spread by proper design of the room surfaces. Interreflections between these surfaces cause the brightness patterns to become more uniform; visibility and seeing comfort are increased.

Windows and other daylight openings that are set flush in a wall or ceiling produce excessive contrasts between exterior brightness and the immediately adjacent interior surfaces. This contrast is often harsh and uncomfortable.

A softer transition is achieved with the use of splayed jambs, rounded jambs, and deep window wells. Instead of the sharp contrast between adjacent surfaces, these designs provide a zone of intermediate luminance to soften the change (figure 5.1). The jambs of the window become light-reflecting shelves that reflect the light indirectly into the interior. Other solutions include using white paint around the windows or hanging draperies or blinds.

For comfortable seeing, the luminance ratio between *fenestration* and adjacent surfaces ought to be less than 20:1. This ratio is also desirable for the surface luminance of

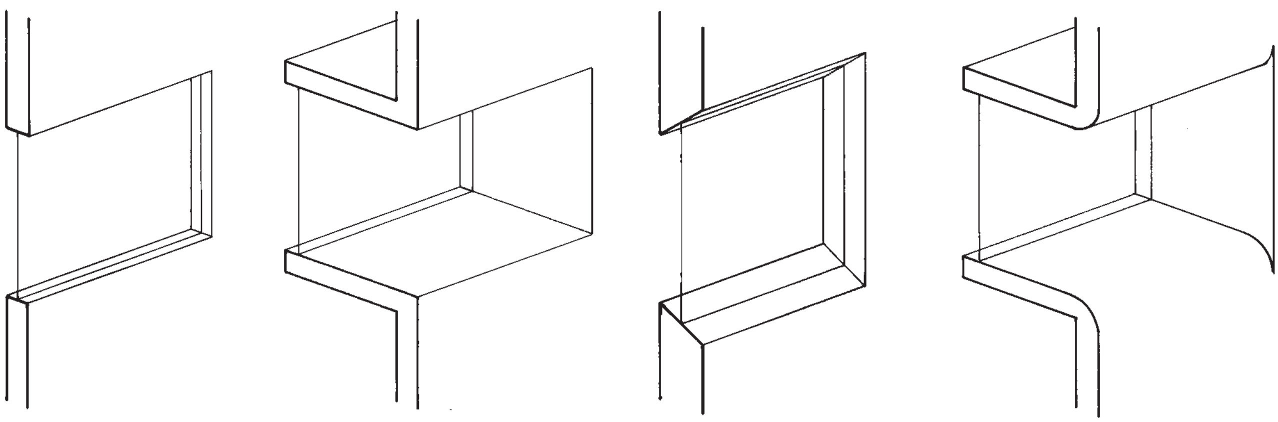


Figure 5.1 Splayed and rounded window jambs soften contrasts.

luminaires and adjacent surfaces. It is advisable to limit luminance ratios anywhere in the field of view to less than 40:1.

Fenestration Sections

Windows placed on a single side of the room (figure 5.2) are the usual method of fenestration. To achieve useful work surface illuminance throughout the room, limit the depth of the room to twice the height from the floor to a full-room-width window head. For example, if the window head height is 10 ft, the optimum room will be no more than 20 ft deep. Somewhat narrower windows provide slightly lower illuminance values, but the difference is minor.

This ratio of 1:2 may be increased to 2:5 as long as the reflectances of interior surfaces are high and carefully controlled. If these ratios are exceeded, people seated in the deepest part of the room will feel as if they are receiving insufficient light, even if they are provided with adequate electric lighting.

Windows placed on opposite sides double the feasible room depth for daylighting. The opposite windows need only occupy the upper part of the wall; the quantity of interior light will be almost the same as if the windows were full height, with the added benefit of reducing the possibility of glare (figure 5.3).

Skylights are tools for delivering daylight deep into interior areas of one-story buildings or into the top floors of multistory buildings. They also bring daylight into the lower floors of multistory buildings through light wells and reflective devices.

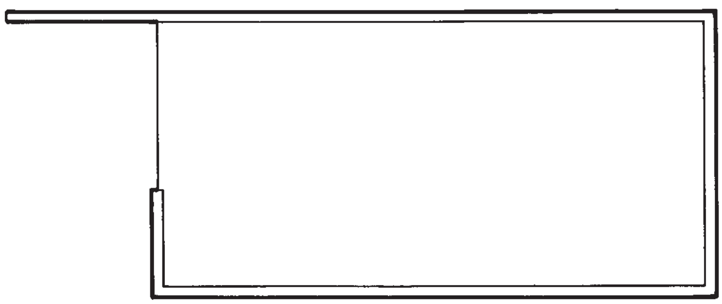


Figure 5.2 Unilateral section.

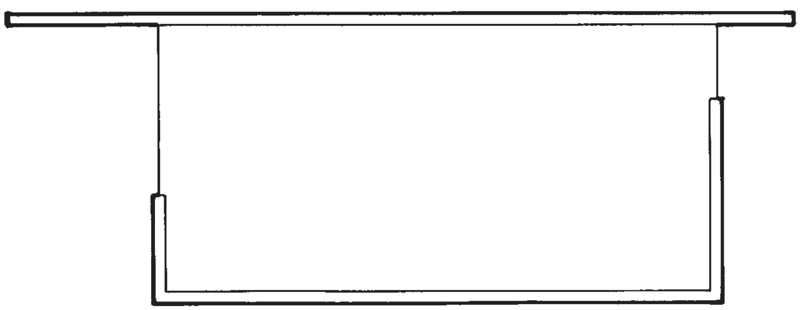


Figure 5.3 Bilateral section.

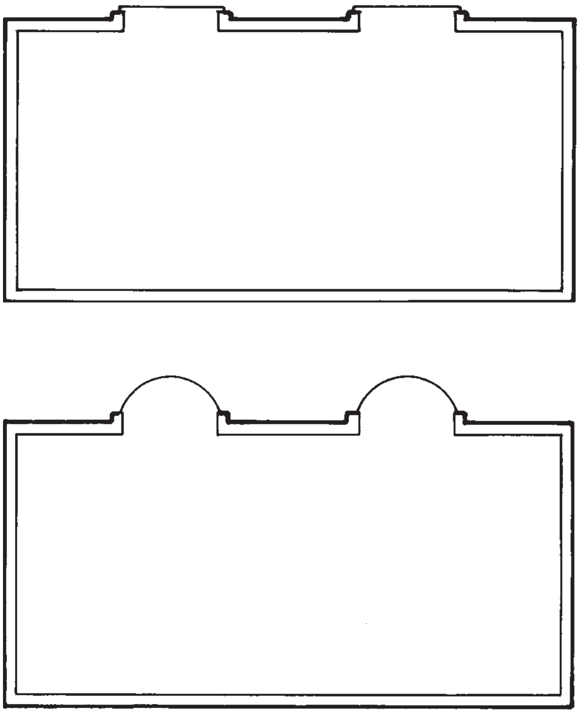


Figure 5.4 Skylight sections.

Skylights come in a variety of shapes and sizes. They are made of clear, patterned, or translucent glass or various kinds of plastic. Clear, gray-tinted, or milk-white acrylics are best for this purpose; their optical properties are similar to glass, and they are easier to maintain.

Flat skylights have both drainage and dirt-accumulation problems. Domed or slanted skylights mitigate these drawbacks (figure 5.4). Although a domed skylight is "self-cleaning" on the outside, dirt still collects on the inside, making a program of periodic cleaning as important with skylights as it is with electric luminaires.

Depending on the shape of the room and the location and size of the skylight, brightness control will be necessary in areas with demanding visual requirements. If directly exposed to view from below, at angles in the *glare zone*, skylights often produce excessive luminance and cause disabling veiling reflections on tasks. Light from skylights is controlled with the use of deep wells, splayed wells, and louvers, preventing any view of the skylight at unsuitable angles and minimizing veiling reflections.

Diffuse (milk-white) plastic or glass skylights diminish the biological benefits of daylight by obscuring the view of the weather. Clear glass or plastic skylights, however, produce more heat gain for a given unit of illuminance at the work surface below and may admit direct sunlight in undesirable ways.

An exterior shield that shades the skylight from direct sun but allows daylight to penetrate reduces the heat load. For colder climates, *double glazing*—two thicknesses of glass or plastic with an air space between—reduces conductive heat loss in winter.

Clerestories have all the attributes of skylights; because they occur in the vertical rather than the horizontal plane, they can be oriented to prevent the penetration of direct sun (figure 5.5). When built in combination with a light shelf, a clerestory reflects great quantities of daylight against the upper ceiling yet blocks the view of the glaring sky from below (figure 5.6).

When facing the same (or opposite) direction as the main windows, the clerestory extends the room-depth limitations (figure 5.7). When clerestories are located on walls opposite each other, as was often the case in early church buildings, these vertical glazing sections are called *roof monitors* (figure 5.8). A series of parallel clerestories is suited for large, low-roofed structures such as factories and warehouses; this is called a *sawtooth* section (figure 5.9).

To maximize the light delivered by the clerestory, it is recommended that the roof directly below the clerestory and the adjacent interior ceiling area be diffuse and highly reflective.

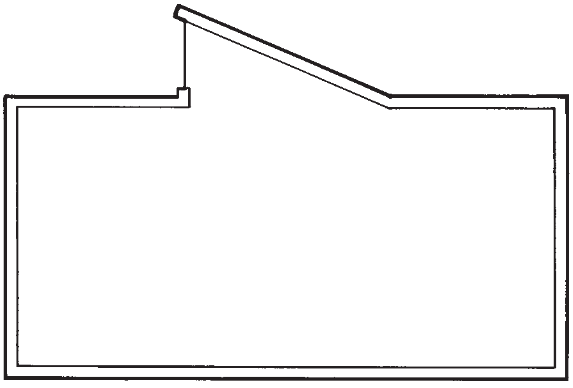


Figure 5.5 Clerestory section.

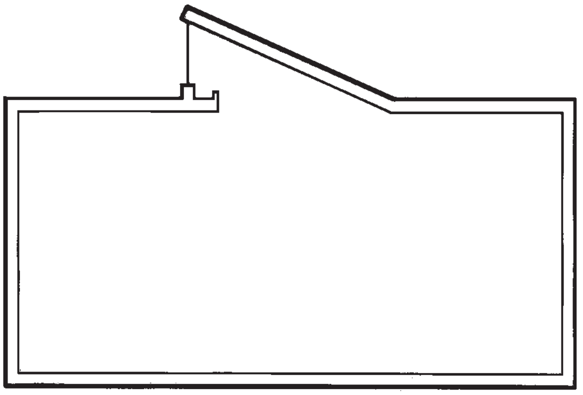


Figure 5.6 Clerestory section with light shelf.

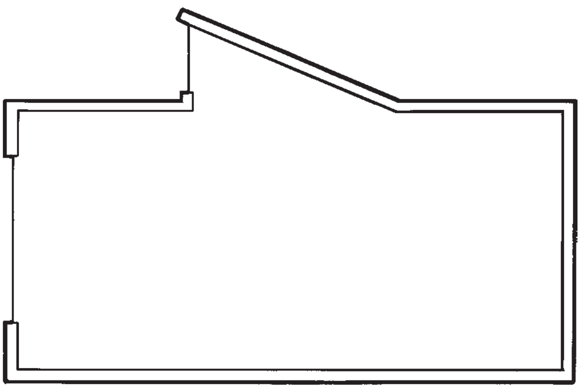


Figure 5.7 Clerestory and main window.

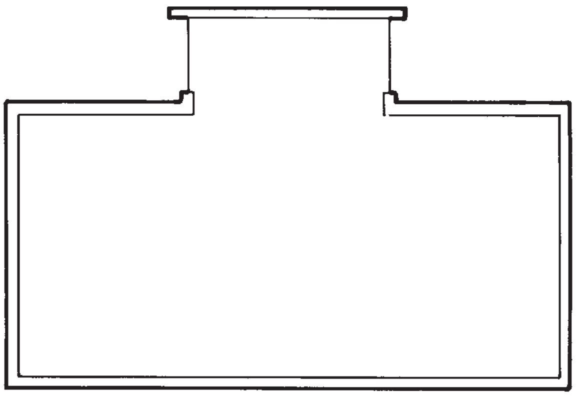


Figure 5.8 Roof monitor section.

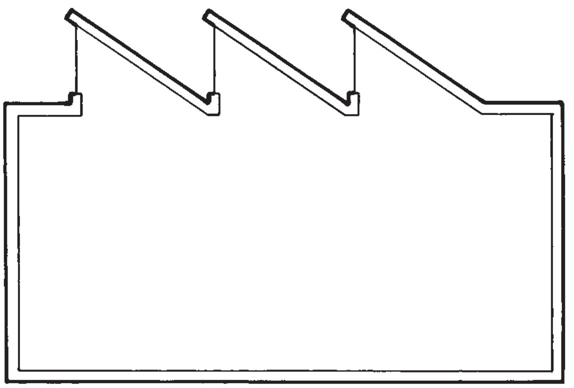


Figure 5.9 Sawtooth section.

Tubular skylights deliver natural light to a room where a traditional skylight or vertical glazing is impractical. They consist of three components: (1) a small, clear acrylic dome located on the roof, which allows sunlight to enter; (2) an adjustable cylindrical aluminum shaft that has been treated with a highly reflective coating; and (3) a translucent diffuser lens located on the interior ceiling, which disperses light throughout the room (figure 5.10).

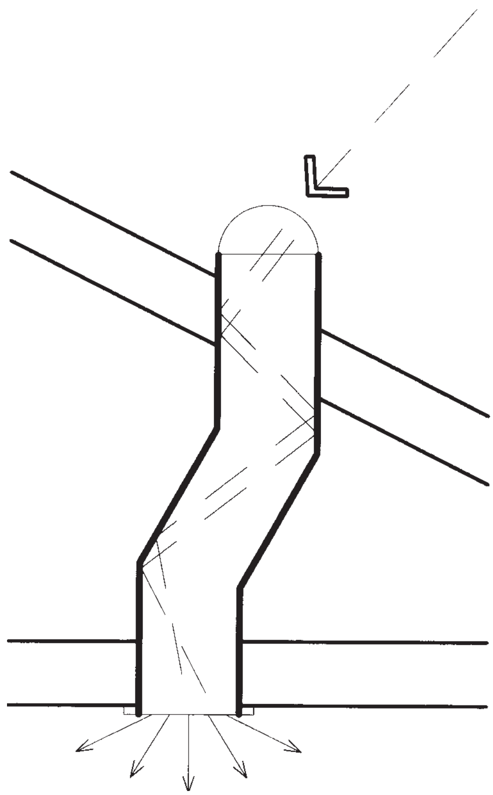


Figure 5.10 Tubular skylight.

The dome is typically installed between rafters and joists on the roof, and the adjustable aluminum tube extends from the roof to the ceiling of the interior. Sold in kits, tubular skylights minimize heat gain and loss: the aluminum tube radiates any collected exterior heat into the attic, and the sealed shaft allows very little interior heat to escape up. Also, little UV is transmitted to the interior; almost all of the UV rays are absorbed by the dome, shaft, and diffuser materials.

Heat Gain

When buildings use glazing to admit daylight, a single layer of ordinary glass exposed to the sun also admits warming radiant energy—heat. This helps in cold winters but poses a problem in hot summers.

If buildings are properly designed to use daylight, they reject most of the direct light from the sun yet still admit an ample supply of skylight. Just as the sun's light can be controlled, there are many ways to control the sun's radiant heat; it may be admitted or excluded as seasonally required without eliminating the benefits of daylighting.

Orientation is a primary method for managing solar heat radiation because the sun strikes differently oriented surfaces with widely varying intensity. The size and placement of glazed areas are also factors in capturing the sun's energy for cold-weather heat gain.

For example, a house benefits if its walls and roof are oriented to receive heat from the sun in the winter and shed it in the summer. If the principal façade of a house faces due south or within 30° of due south, the south-facing walls may be designed to absorb radiation from the low winter sun; the roof may be designed to reject the sun's heat by reflecting the high summer sun.

It is possible with any building orientation to achieve good quality daylighting indoors. North light is inherently softer, cooler, and more uniform; because of the sun, south light is more intense and variable. But the same high quality of illumination that comes naturally from the north sky can be achieved with any other orientation by the proper use of daylight controls.

SHADING DEVICES

Shading devices used on the inside of the building reflect some of the radiant heat energy back outdoors, reducing the energy gain from the sun by as much as 60 to 70 percent. Exterior shading devices can reduce that energy penetration even more—by 90 to 95 percent. Exterior shading devices are more expensive to build and maintain, but with hot climates or high energy costs or both, air-conditioning savings often give quick paybacks.

A variety of shading devices are employed to deliver daylight to where it is needed and to reduce glare by limiting excessive luminance in the field of view. Shading devices are divided into two categories: movable and stationary.

Movable controls adjusted in response to varying sky conditions are the most efficient, but they require a human operator or an automatic device. Stationary (static) controls are less expensive but are also less efficient, because they are unresponsive to daily and seasonal changes.

Movable Controls

Draperies, shades, and screens are available with a wide range of materials that vary in their openness of weave and surface reflectivity. They provide almost any desired degree of light transmission or a complete blackout. Greater flexibility is achieved with two separately tracked draperies over a window area—one used to reduce light and the second to block it completely.

Light-colored *venetian blinds* (interior horizontal louvers) can be adjusted to exclude direct sunshine but reflect light to the ceiling, increasing its penetration into the space while still allowing a view of the outdoors (figure 5.11). Or they can be closed completely, blocking both light and view.

But for venetian blinds to function appropriately under changing sky conditions, they must be operated with an understanding of their potential by someone who has the opportunity and the incentive to perform the task. Venetian blinds collect dirt easily and are tedious to clean; they are subject to mechanical failure of support straps and control strings.

Double-glazed windows are available with a narrow venetian blind positioned between the inner and outer glass, which eliminates the dirt-collection problem. These blinds are fully operable and reject heat more efficiently than interior blinds or other shading devices such as roller shades or draperies.

Motorized controls allow convenient adjustment of sun-filtering and light-blocking fabrics on windows and skylights. They permit one-touch adjustment of blinds and draperies for changing activities or changing sun, or they can be programmed to move fabrics with the sun automatically.

Motorized controls may be linked to home or building automation systems, so that shades move at preset times or at specific illuminance values. They can also combine control of daylight with electric light so that sun-filtering or light-blocking fabrics and electric lights are adjusted at the same time.

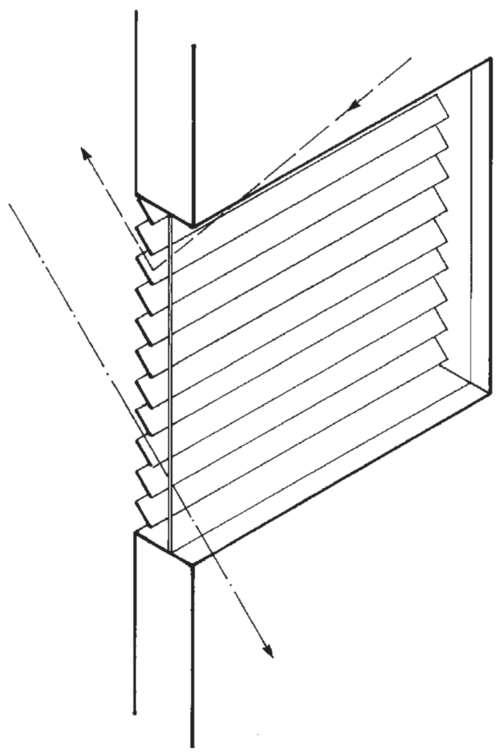


Figure 5.11 Properly adjusted venetian blinds reflect daylight to the ceiling and do not prevent a view outside.

Exterior motorized shades place the sun-filtering fabrics on the exterior of a window, providing solar protection by stopping excessive glare, UV rays, and heat before they enter a building. Movable shading devices on building exteriors are difficult to maintain, however, and they deteriorate rapidly unless made of a copper alloy or stainless steel. Awnings are highly reliable, but their aesthetic appeal is limited.

Stationary Controls

Fixed awnings and building overhangs serve to shade direct sunlight and reduce glare through the upper area of windows (figure 5.12). They also reduce the daylight entering the room, decreasing the illumination close to the window and the penetration into the room. The maximum depth of useful light penetration is calculated from the outer edge of the awning or overhang instead of the vertical plane of the window.

Although they reduce the quantity of skylight entering the building, overhangs can collect light from a light-colored exterior surround and reflect it into the interior. This results in a more even distribution of light.

An overhang located on the southern side of a building is especially efficient at controlling both light and heat from the sun (figure 5.13). In the summer, the overhang shields the glass from the sun's direct rays yet allows daylight to enter from the lower sky and by reflection from the ground. In the winter, the overhang allows the low-angle sun to penetrate for warmth, but seating must be oriented to avoid direct sun glare.

Exterior horizontal louvers may pick up direct sun, causing excessive luminance and discomforting or disabling glare (figure 5.14). Exterior or interior vertical louvers are useful for low sun angles that occur in the early morning or late afternoon, particularly on building walls oriented toward the east or west (figure 5.15). When it is necessary to control both high sun and low sun, "egg-crate" louvers are used because they combine horizontal and vertical shielding.

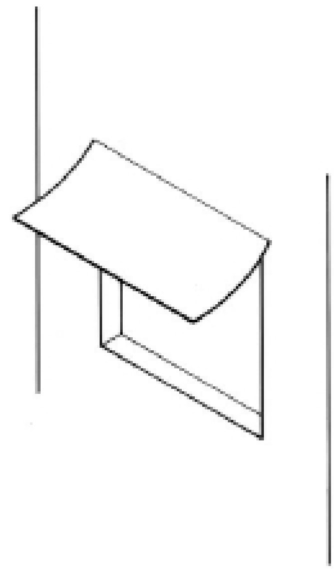


Figure 5.12 Awning.

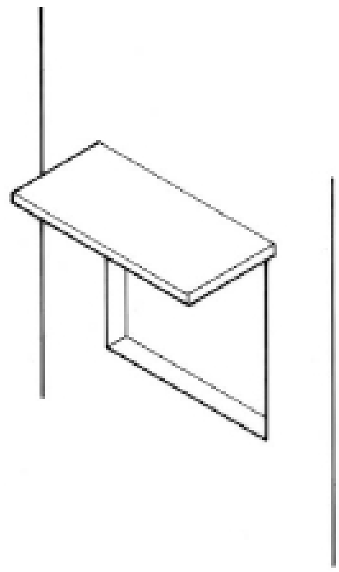


Figure 5.13 Overhang.

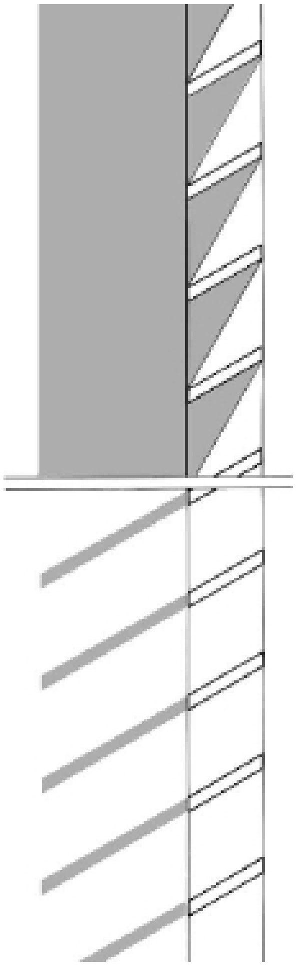


Figure 5.14 High sun and low sun angles at exterior louvers.

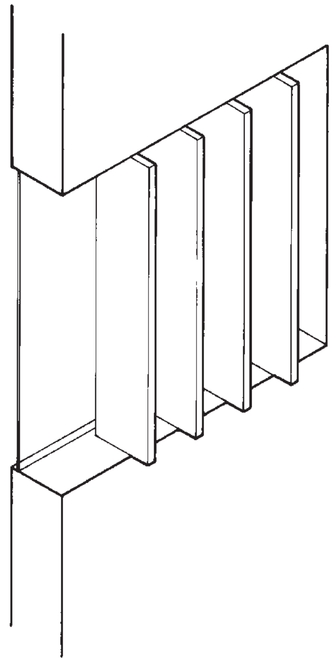


Figure 5.15 Vertical louvers.

Direct sunshine from flat skylights or from pitched skylights facing east, south, or west must also be controlled. Interior louvers or translucent shades will reduce glare and heat, but exterior controls provide superior shading.

Exterior sun shades can be oriented to shade light and heat from the sun during warm weather yet allow penetration during the cold seasons, or be designed to eliminate direct sun from the interior all year long (figure 5.16).

A difficulty with fixed overhangs and awnings is that the amount of shading follows the solar seasons rather than the climatic seasons. The middle of the summer for the sun is June 21, but the hottest days occur from the end of July to the middle of August. The overhang designed for optimal shading on September 21, when the weather is still warm and solar heat gain is unwelcome, causes the same shading on March 21, when temperatures are lower and solar heat gain is welcome (figure 5.17).

Vegetation, which follows the climatic seasons, provides excellent shading year-round. On March 21, many plants are without leaves and do not obstruct the passage of sunlight. On September 21, however, the leaves are still full and provide good shading. Deciduous trees or an overhanging trellis with a climbing vine that sheds its leaves in

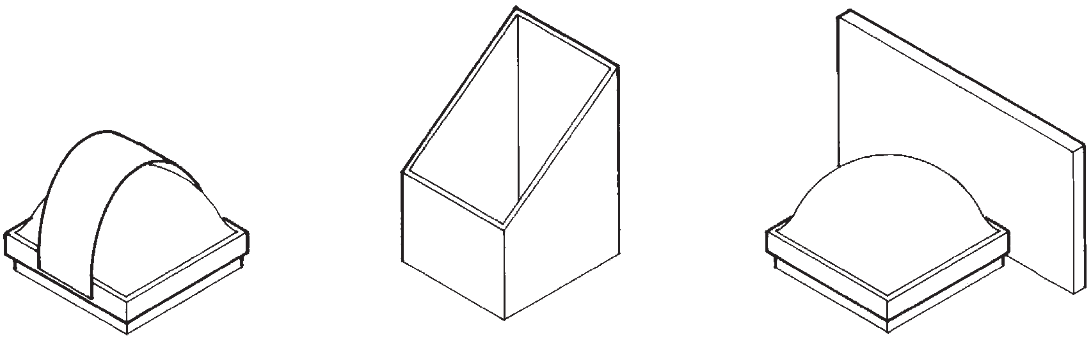


Figure 5.16 Skylight shades.

winter provide natural climatic control when placed in front of south-facing windows.

GLAZING MATERIALS

Glazing materials are available with a wide range of heat and light transmittance, color, and prismatic control. Because of its resistance to abrasion, glass is the preferred material; where breakage is a concern, acrylic or polycarbonate is substituted. Both glass and plastic can be tinted in warm, neutral, or cool gray tones to reduce the transmission of light and heat yet remain transparent to vision. Saturated colors are to be avoided except in carefully designed art ("stained") glass windows.

Translucent glazing materials that transmit diffused light but obscure vision include etched, sandblasted, opal, and patterned glass and plastic. Many translucent materials become excessively glary with exposure to the sun and will be distracting when seen from task areas. Because they prevent a view of the outside, their psychological value is minimal. As diffusion increases so does the area of luminance and the possibility that the window or skylight will become a source of glare.

Selectively transmitting materials allow the desirable wavelengths of the visible spectrum to pass but reflect or absorb the radiant heat energy. Directionally selective glass blocks and prismatic glass or plastics refract light for directional control.

When installed vertically, prismatic glass block walls are used to reflect daylight onto the ceiling of a room, increasing illuminance values deep in the interior and removing the glaring sky from view (figure 5.18). When installed horizontally, as with glass-block pavers, they transmit light yet maintain a low surface luminance even when exposed to direct sun.

QUANTITY

Because of the great variety of changing sun and sky conditions, it is impractical to predict precisely the interior illuminance patterns derived from daylighting. By knowing the size and position of windows and using tables of average daylighting conditions for various locations and orientations, the average amount of available daylight that will enter a space can be determined, but not the precise amount at any moment.

Interior daylight illuminance values are often expressed as a daylight factor. The daylight factor accounts for light received directly from the sky, light reflected from external surfaces, and interreflections within

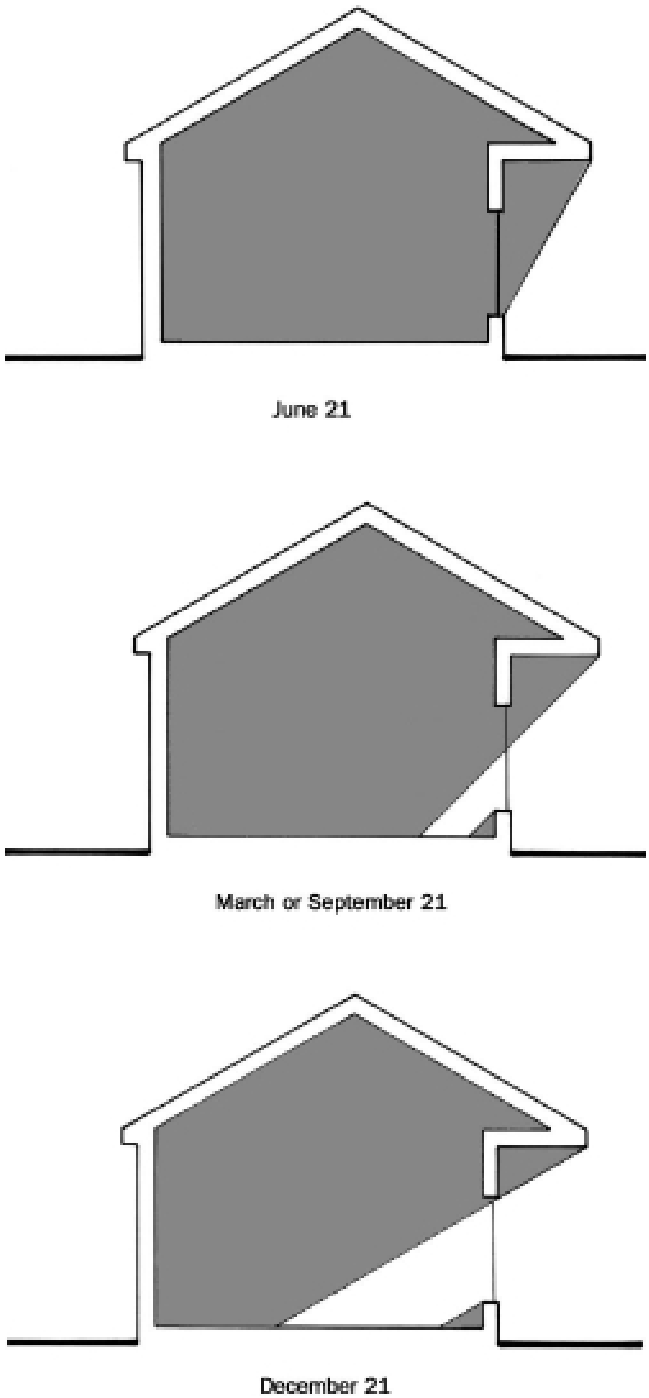


Figure 5.17 Shading a south window with a fixed overhang (at solar noon).

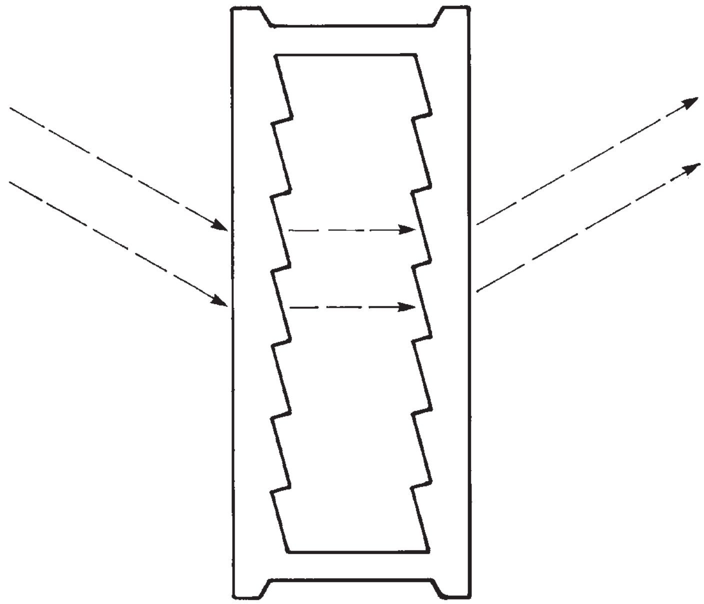


Figure 5.18 Prismatic glass block directs daylight toward the ceiling.

the room. It is a measure of the proportion of the outdoor illumination to the daylight illumination received indoors.

Average interior daylight illuminance is also calculated by graphic methods, such as the Libbey-Owens-Ford™ "Sun Angle Calculator," and by computer programs that consider geographic location, time of day, time of year, fenestration, room shape, and interior finishes. The most sophisticated programs produce a rendering of the interior showing the relative luminances of room surfaces.

The simplest, most versatile, and most reliable technique for studying the aesthetics of daylighting is simulation by construction of a scale model. Daylight behaves in the same way in a scale model as in an actual building. If studied under similar sky conditions, the interior of the scale model appears exactly as will the interior of the building. Miniature photo electric cells are placed inside the model to read illuminance values. But identical sky conditions are difficult to achieve by placing the model outdoors; this has led to the development of sky simulators that can reproduce almost any sky condition.

ENERGY CONTROL

Photosensors (light-sensing devices) automatically switch electric luminaires off when the daylight contribution at selected interior locations reaches prescribed levels. The luminaires are automatically switched on as the available daylight decreases. This kind of switching has the disadvantage of calling undue attention to the change; it may be abrupt and jarring.

Dimming systems that allow a gradual increase and decrease in light quantity are more satisfactory. This is more pleasant and may even go unnoticed. Sophisticated systems are designed with a built-in delay so that a cloud passing rapidly across the sun triggers no response.

Incandescent Lamps 6

The incandescent lamp is a simple device—a hot wire (the filament) sealed in a glass jar (the bulb).

An electric current passing through the wire heats it to incandescence, and the wire emits light. The filament wire diameter and length determine the amount of electrical current drawn by the lamp, regulating its light output (figure 6.1).

The incandescent lamps discussed in this chapter are commonly referred to as "large" lamps. This designation does not refer to large physical size, but has traditionally described lamps that operate on standard-voltage circuits. The "large lamp" category now includes lamps of many voltages commonly found in residential, commercial, and industrial use.

"Miniature" lamps, conversely, are not necessarily small, although many of them are. They are lamps that operate at less common voltages, powered by storage batteries or by transformers that reduce or increase the standard voltage to the voltage required by the lamp. Their predominant use is in transportation vehicles and instruments.

The family of large lamps contains about one hundred combinations of glass and quartz bulb shapes and sizes. These variations are designated by a two-part abbreviation: the first part, one or more letters, indicates the shape of the bulb; the second part, a number, indicates the diameter of the bulb in eighths of an inch. For example, an A19 lamp is an *a*rbitrary-shaped lamp that is $^{19}\!/_8$ ($2^3\!/_8$) inches in diameter (figure 6.2).

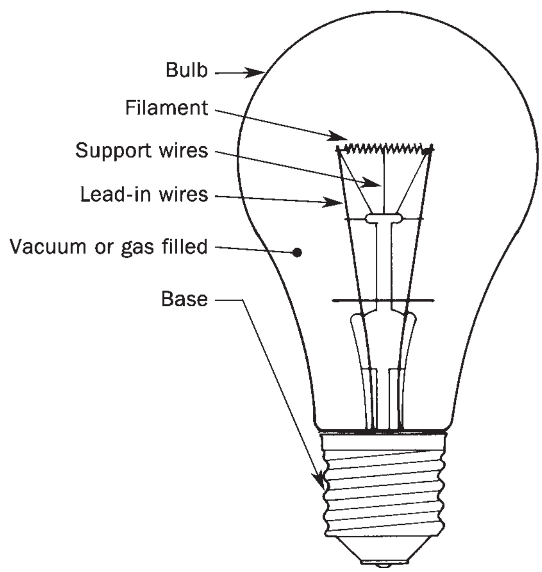
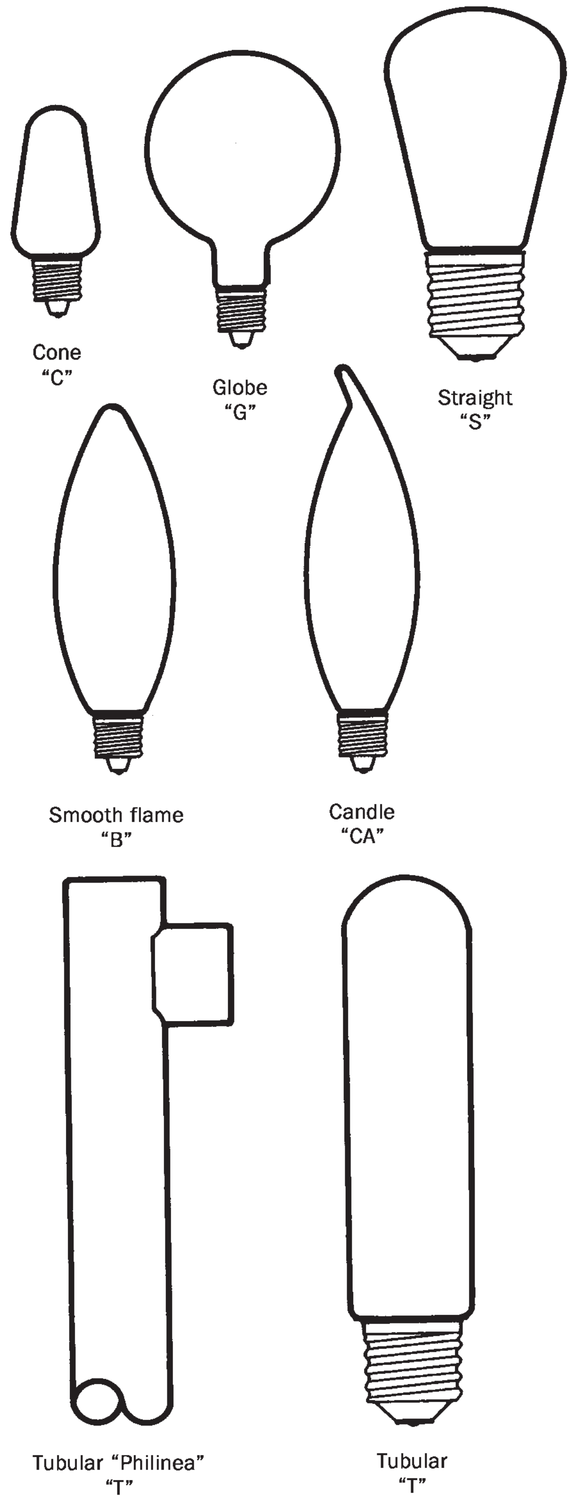


Figure 6.1 Incandescent lamp components.

A	*a*rbitrary (with familiar teardrop shape)
AR	*a*luminum *r*eflector
B	flame (smooth)
C	*c*one shape
CA	*ca*ndle
F	*f*lame (irregular)
G	*g*lobe shape
GT	*g*lobe–*t*ubular
MR	multifaceted *m*irror-*r*eflector
P	*p*ear shape
PAR	*p*arabolic *a*luminized *r*eflector
PS	*p*ear–*s*traight neck
R	*r*eflector
S	*s*traight side
T	*t*ubular



LAMP BASES

Incandescent lamps have a base at one end, although some tubular lamps have bases at both ends. All bases conduct current from the electrical supply into the lamp (figure 6.3); most bases also support the lamp physically, but many kinds of PAR lamps can be supported by their bulbs.

The most frequently used is the medium base; its name describes its size. Smaller lamps have smaller bases, including *bayonet, bipin, candelabra, intermediate, miniature, mini-candelabra ("mini-can"), twist-and-lock (TAL),* and *two-pin* bases. Larger lamps have larger bases, including *mogul* screw and medium and mogul *bipost* bases. The bipin and bipost bases orient the filament position, providing rotational alignment for optical control. Bayonet and *prefocus* medium and mogul bases also locate the filament in the exact predetermined position required for optical instruments and searchlights.

FILAMENTS

All incandescent lamps contain a filament, which is more or less centered within the bulb. A filament is a length of tungsten wire; tungsten is used because of its high melting

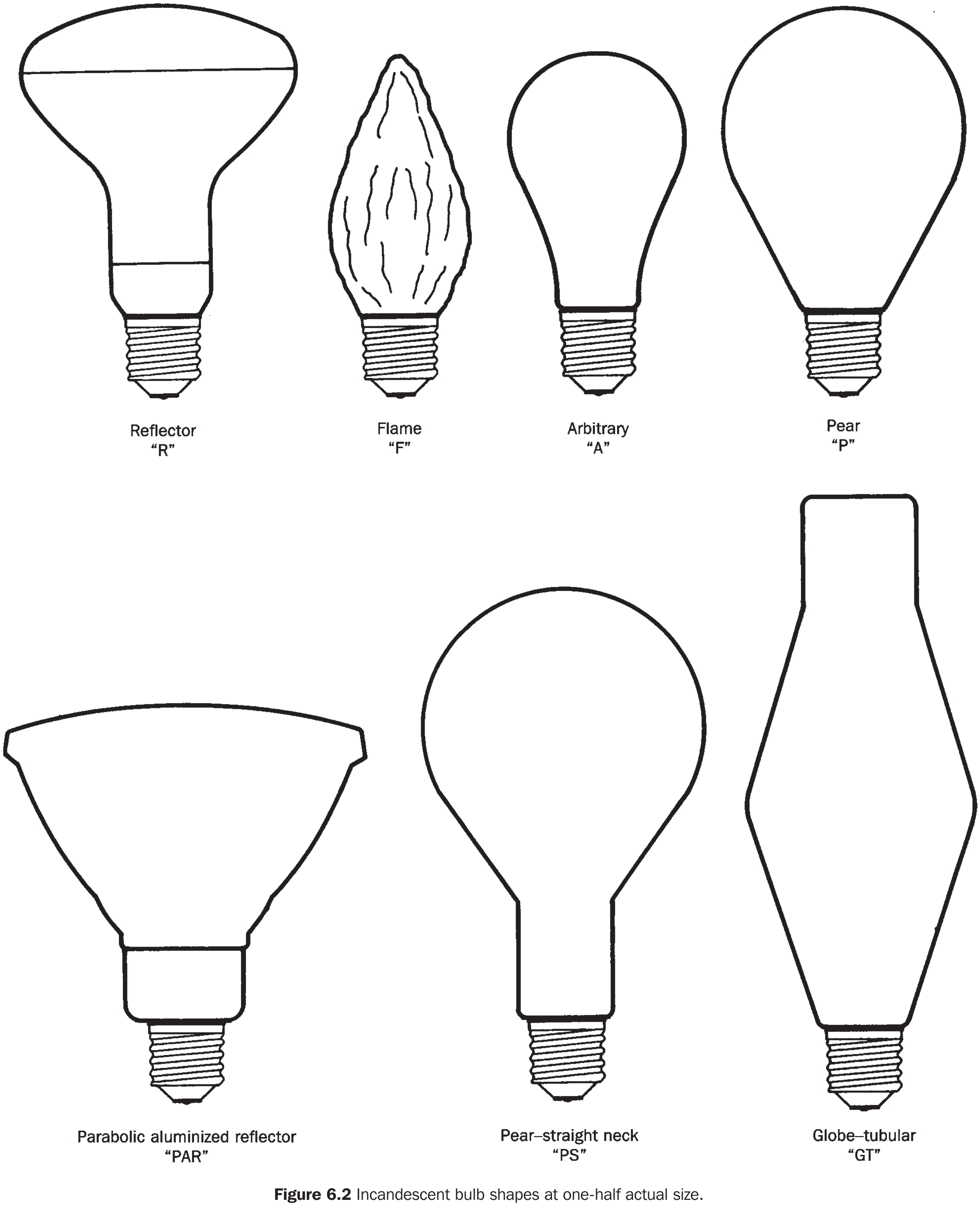
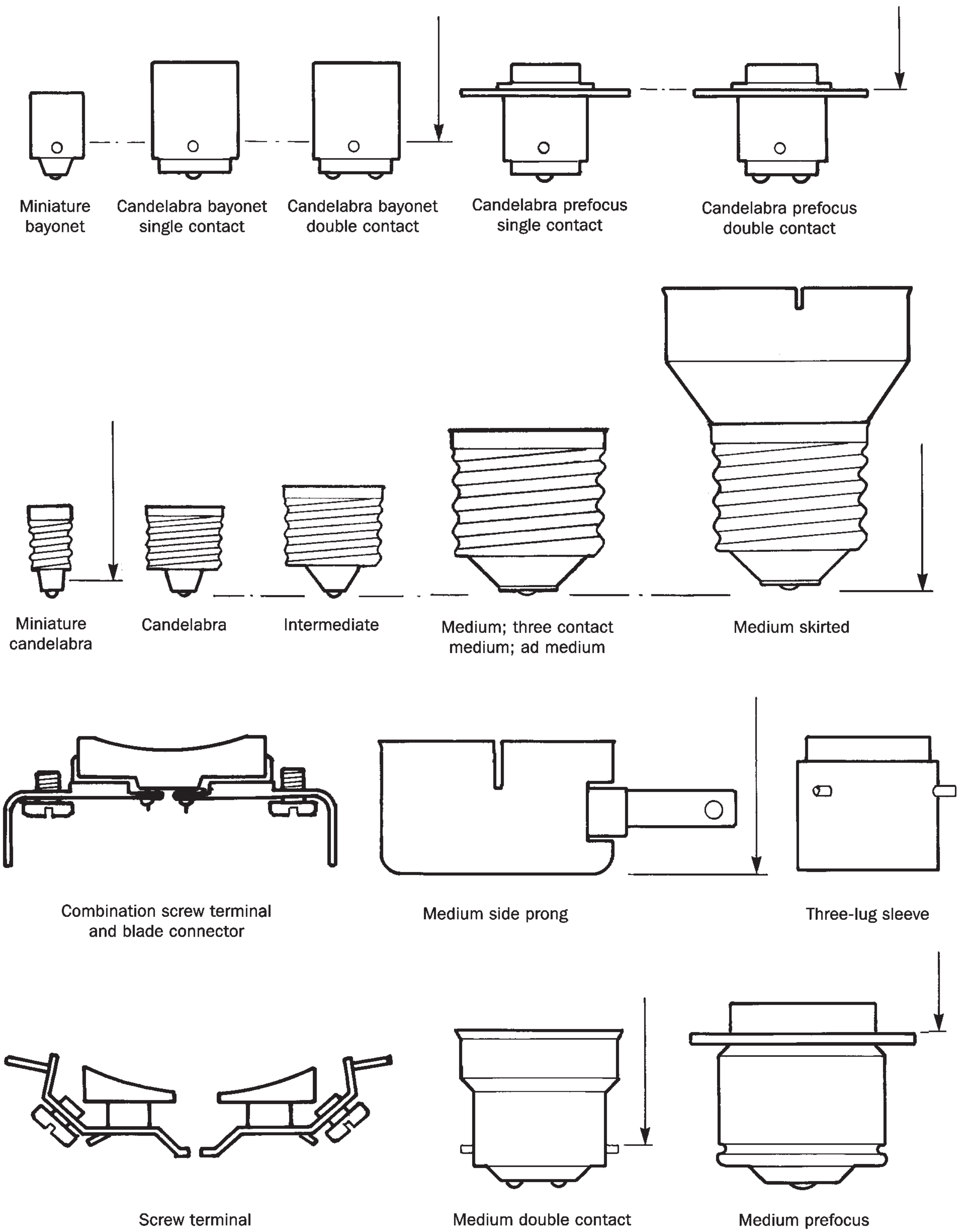


Figure 6.2 Incandescent bulb shapes at one-half actual size.


Miniature bayonet
Candelabra bayonet single contact
Candelabra bayonet double contact
Candelabra prefocus single contact
Candelabra prefocus double contact
Miniature candelabra
Candelabra
Intermediate
Medium; three contact medium; ad medium
Medium skirted
Combination screw terminal and blade connector
Medium side prong
Three-lug sleeve
Screw terminal
Medium double contact
Medium prefocus

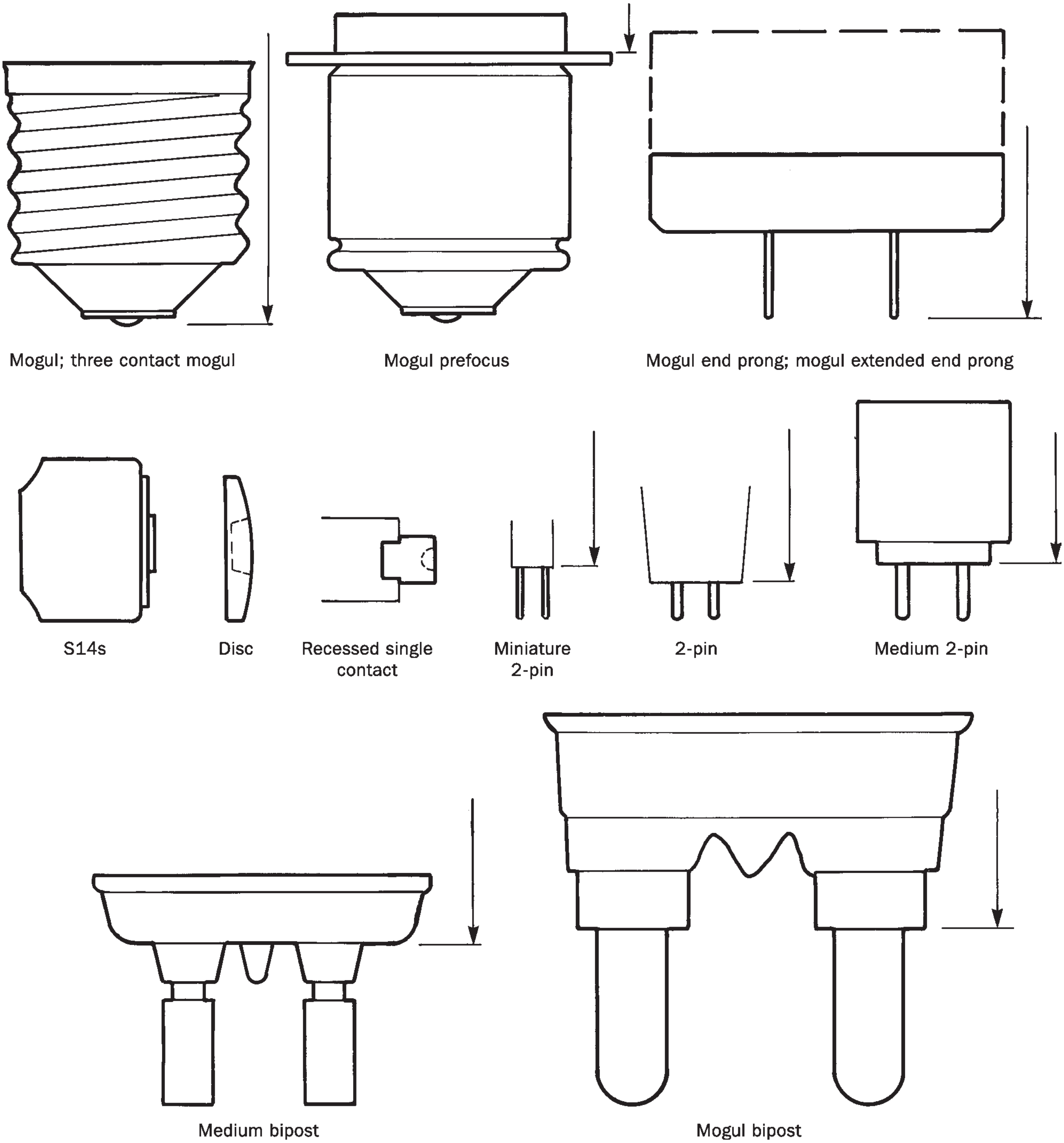


Figure 6.3 Incandescent lamp bases at one-half actual size. The arrow indicates the point from which the light center length (LCL)—the dimension from the filament to a designated point that varies with different base types—is measured.

temperature. Occasionally the wire is straight, but usually it is coiled to pack more length into a small envelope, concentrating light and heat and increasing efficacy. Coiled filaments are designated by the letter *C*. Sometimes the coil itself is coiled and designated *CC* for "coiled coil."

Filament design is determined by striking a balance between light output and lamp life. It is a function of filament temperature: the higher the temperature at which the filament operates or "burns," the more light it emits and the shorter its life—the sooner it fails or "burns out." A long-life lamp of a given wattage produces less light than a standard-life lamp of the same wattage, which consumes the same current but is designed for a shorter life.

Lamp efficacy is the ratio of light produced (measured in *lumens* [lm]) to electricity consumed (measured in *watts* [W]). Lamp life is measured in hours (hr).

LIGHT OUTPUT

Lamp bulbs do not contain air, because the incandescent tungsten will react with the oxygen in the air and quickly evaporate. Originally this was prevented by creating a vacuum in the bulb. Today, filling the bulb with an inert gas slows bulb blackening, which is caused by condensation of evaporated tungsten particles on the inner bulb wall. Argon, nitrogen, and krypton gases are used for this purpose. (Some incandescent lamps, particularly those below 40 W, still use a vacuum.)

Although reduced by the inert gas pressure, the filament evaporation continues throughout life; the tungsten wire becomes thinner, consumes less power, and emits less light. This light loss combined with bulb blackening causes a steady decrease in light output throughout the life of the lamp.

A reciprocal relationship exists between light output and life. Over-voltage operation results in higher wattage, higher efficacy, and higher light output, but shorter lamp life. Under-voltage burning results in lower wattage, lower efficacy, and lower light output, but longer lamp life (figure 6.4). As a rule of thumb, a given percentage reduction in wattage is accompanied by double that percentage reduction in light.

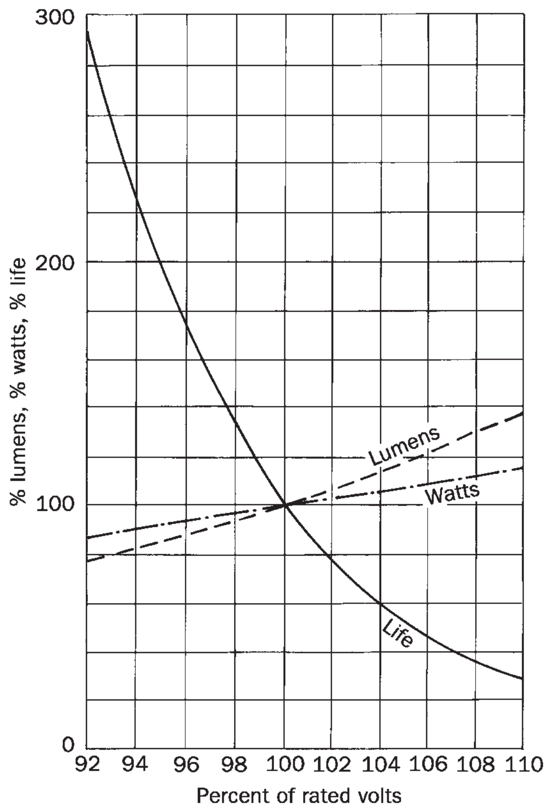


Figure 6.4 Incandescent lamp characteristics as affected by voltage (V). For example, operating a 120 V lamp at 125 V means approximately 16% more light (lm), 7% more power (W), and 42% less life (hr). Operating a 120 V lamp at 115 V means approximately 15% less light (lm), 7% less power (W), and 72% more life (hr).

Incandescent lamps are usually sold by wattage, but a watt is not a measure of light—it is a measure of power consumed. With electric light sources, it is a measure of how much electricity the lamp uses during operation. Lumens tell how much light a lamp emits.

Extended-service (2,500-hr) incandescent lamps achieve their longer life by a reduction in light output and efficacy. Lumen output is approximately 15 percent less than standard 750-hr and 1,000-hr life lamps. These lamps are more expensive than standard ones, but their longer life is useful in locations that are difficult to relamp.

Many energy-saving or “watt-saving” lamps are simply reduced-wattage lamps. The reduced power consumption is accomplished by a reduction in light output. Some energy-saving lamps have a more efficient filament design, gas fill, or reflector bulb shape to maintain light output.

LAMP TYPES

Incandescent lamps are divided into three categories according to their ability to direct light: (1) nondirectional sources emit light in all directions and require additional components to control their distribution, (2) semi-directional sources give a direction to their light output and require additional components to complete a spatial distribution, and (3) directional sources control the distribution of emitted light and require no additional components, being complete optical systems in themselves.

Nondirectional Sources

Nondirectional lamps emit light in all directions. They include A, C, G, P, PS, S, and T shapes and decorative lamps. These lamps require external elements in the form of a lens, reflector, or shield to modify their distribution and to control their brightness (figure 6.5).

To reduce the glare from an exposed filament, many nondirectional lamps have a coating applied to the inner surface of the clear bulb. A two-bath acid etch or a light coating of electrostatically applied white powder absorbs an insignificant amount of light, yielding a ball of light inside the bulb. This kind of lamp has lower luminance and less glare than the exposed filament. It is called an *inside-frost* lamp (figure 6.6).

Still greater diffusion, with a further reduction of glare and a sacrifice of about 2 percent of the light output, is achieved by a double coating of white silica powder. This gives a ball of light the size of the lamp, yielding a bulb of almost uniform brightness. It is called a *soft-white* lamp.

In both treatments, the outer surface of the bulb is left smooth, which makes it easy to clean. Inside-frost lamps are preferred for most luminaires to reduce the sharpness of shadows and the possibility of striations on nearby surfaces. Where the small point source contributes to glitter, as in the sparkle of crystal chandeliers, clear lamps are necessary.

Semi-Directional Sources

The category of *semi-directional* sources includes silver-bowl and white-bowl lamps. *Silver-bowl* lamps, usually used to direct light upward, have an opaque silver coating applied to the inside of the bowl (figure 6.7). This functions as a specular reflector that remains clean, and therefore efficient, throughout the life of the lamp. Silver-bowl lamps are available in both clear and inside frost.

When used indirectly in a suspended luminaire to light the ceiling, the upper part of the bulb must be concealed to prevent excessive brightness and glare. This is accomplished by an assemblage of circular rings around the lamps or by a shallow, diffusing glass bowl. When silver-bowl lamps

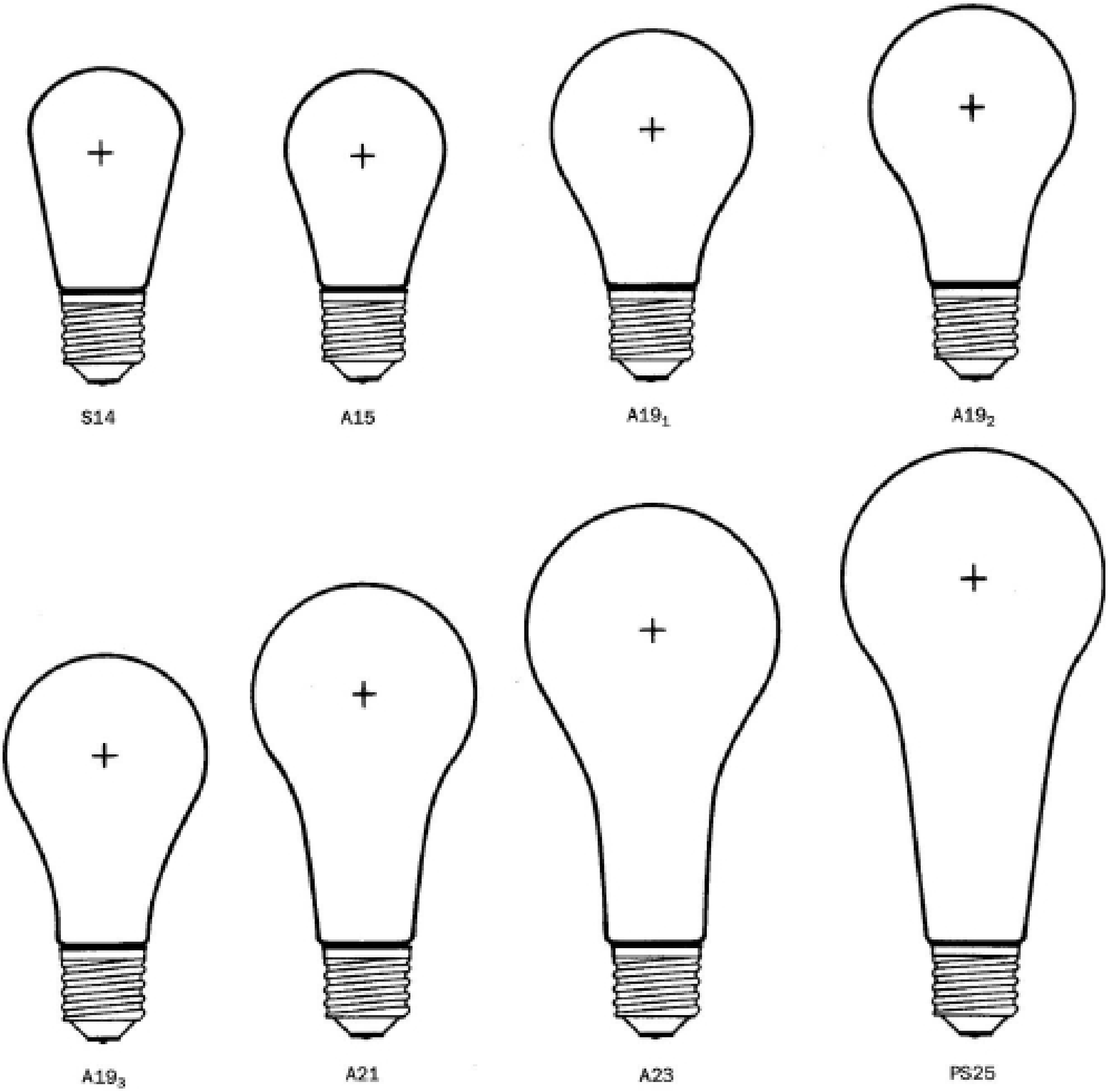


Figure 6.5 A-shape lamps at one-half actual size. Maximum Overall Length (MOL): maximum end-to-end length of the bulb within tolerances stipulated by the American National Standards Institute (ANSI). Actual length may be less. Light center length (LCL): the distance from the center of the filament to a designated point that varies with different base types.

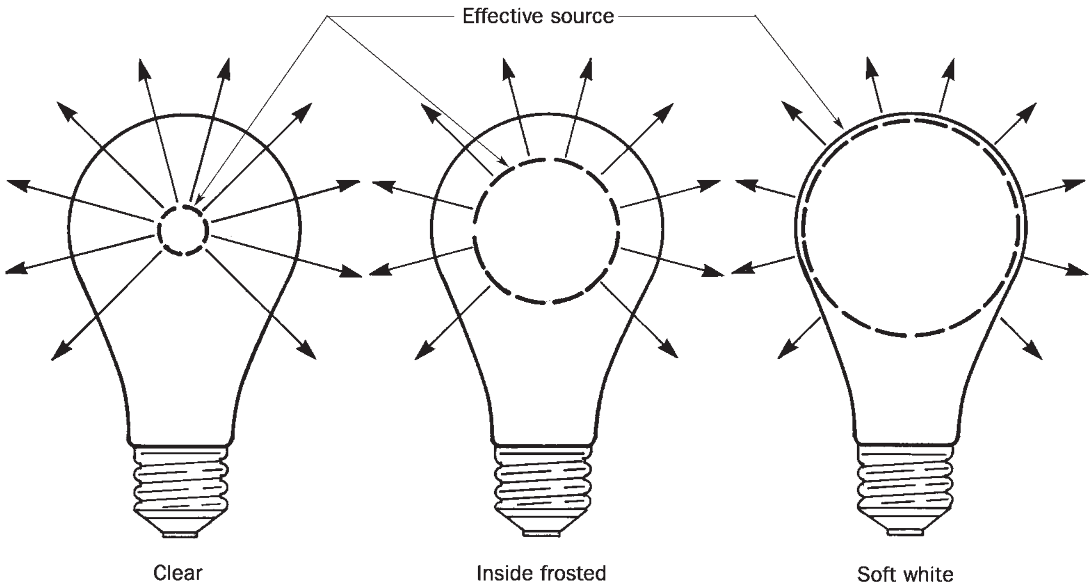


Figure 6.6 Clear, inside-frosted (acid-etched), and soft-white (silica-coated) lamps.

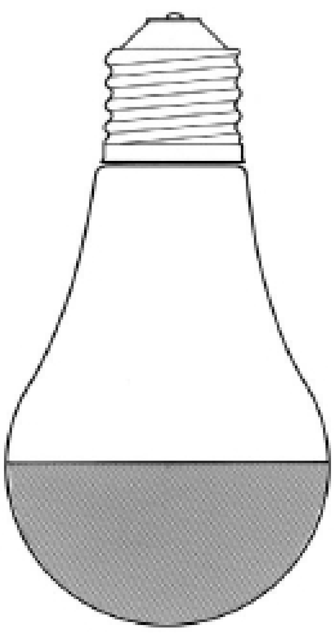


Figure 6.7 Silver-bowl lamp.

are used in recessed luminaires, the upward light emitted by the lamp is redirected in a downward direction by a secondary reflector.

White-bowl lamps, also used for indirect lighting, have a translucent white coating on the inner surface of the bulb bowl, which reduces the direct filament glare. As with silver-bowl lamps, white-bowl lamps require additional control elements.

Directional Sources

Directional sources are lamps that are complete optical systems; they include a source (the filament), a reflector, and sometimes a lens or a filament shield. Lamps in this category are *r*eflector (R), *a*luminum *r*eflector (AR), multifaceted *m*irror-*r*eflector (MR), and *p*arabolic *a*luminized *r*eflector (PAR). These directional sources are available in a wide range of wattages and beam-spreads, as indicated in table 2 in the Appendix.

R lamps

In *reflector* (R) lamps, the bulb is shaped into a reflecting contour; the inner surface is coated with vaporized silver. The lamps are available in spot or flood beam-spreads. Spot lamps have a light frost on the inside front of the bulb; flood lamps have a heavier frosting to increase the spread of the beam.

As with nondirectional and semi-directional incandescent lamps, the glass bulbs of most R lamps are made of blown lime glass. This "soft" glass is intended only for indoor use. Some wattages are available in a "hard," heat-resistant glass for areas where contact with moisture is a possibility, but these lamps still require protection from rain.

All R lamps emit a substantial percentage of light outside the principal beam. Unless intercepted by an auxiliary reflector, this light is usually lost due to absorption within the luminaire; in most luminaires, R lamps are inefficient.

AR and MR lamps

See low-voltage lamps, pages 75 to 77.

PAR lamps

Parabolic aluminized reflector (PAR) lamps are made of low-expansion, heat-resistant borosilicate glass that is pressed rather than blown. This method of construction allows great precision in shaping the reflector of the bulb and in the configuration of the lens, as well as in the positioning of the filament. The combined precision of these factors accounts for the superior beam control and greater efficacy that are characteristic of PAR lamps (figure 6.8).

PAR lamps were originally designed for outdoor applications and are sometimes still referred to as "outdoor" lamps because they are weather-resistant. Over the years their use indoors has grown rapidly wherever efficacy and precise beam control are desired.

PAR lamps are available with beam-spreads that range from 3° (very narrow spot, or VNSP) to 60° (very wide flood, or VWFL). The initial beam is formed by the shape of the reflector and the position of the filament. The configuration of the lens modifies that beam: a light stipple smoothes the narrow beam for a spot lamp; "prescription" lenses similar to those of car headlights provide the wider beam distributions of flood lamps.

In *cool-beam* PAR lamps, a reflective dichroic coating replaces the bright aluminum used on the reflector surface of standard PAR lamps. Visible wavelengths (light) are reflected forward into the beam while infrared wavelengths (heat) pass through the back of the bulb. About two-thirds of the heat energy in the beam is removed; light output and distribution are unchanged. These lamps were originally developed to light perishable foods (figure 6.9).

EPACT

The U.S. Energy Policy Act of 1992 (EPACT) established minimum average efficacy standards for certain incandescent R and PAR lamps that operate at 115 to 130 V and have medium bases and diameters larger than 2¾ in. Most incandescent R30, R40, and PAR38 lamps do not meet the criteria; tungsten-halogen PAR lamps do. Colored lamps and rough- and vibration-service lamps are exempt from the efficacy standards. The act does not prescribe standards for other kinds of incandescent lamps.

As of 31 October 1995, the following lamps are prohibited from manufacture or sale in the United States: 75R30; 75-, 100-, 120-, and 150R40; and 65-, 75-, 85-, 120-, and 150PAR38. These efficacy standards, measured in lumens per watt, were established according to lamp wattage. This approach ignores the function of the luminaire, however: an inefficient, incandes-

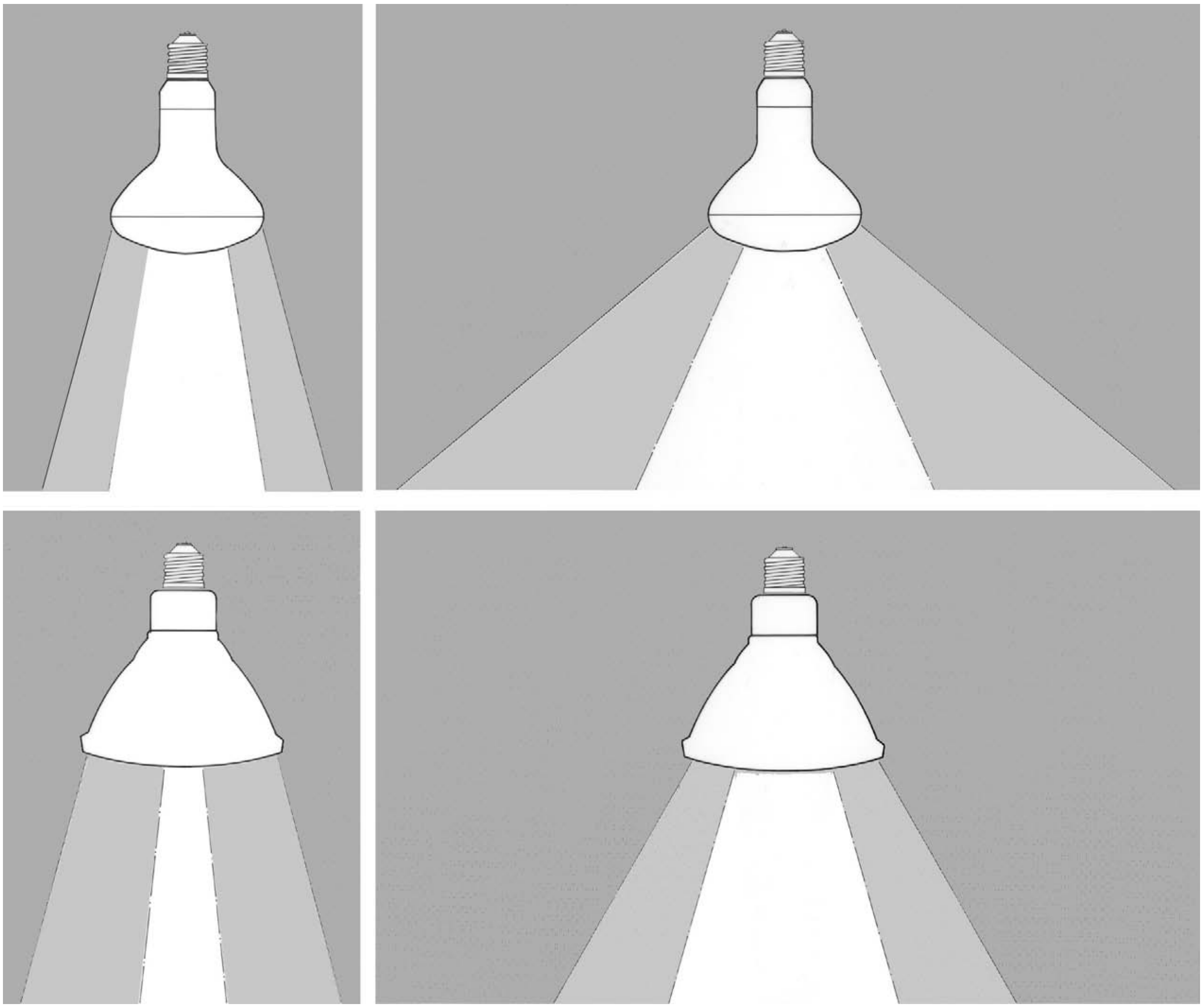


Figure 6.8 R and PAR spot and flood lamp beam-spreads.

cent R lamp with a well-designed reflector can be more efficacious than the most efficient, tungsten-halogen PAR lamp in a light-wasting, multi-groove-baffle downlight.

TUNGSTEN-HALOGEN LAMPS

The *tungsten-halogen* (or *halogen*) lamp is an incandescent lamp with a selected gas of the halogen family sealed into it. As the lamp burns, the halogen gas combines with tungsten molecules that sputter off the filament and deposits the tungsten back on the filament, rather than on the bulb wall. This keeps the bulb wall clean and at the same time builds up the filament wire to compensate for the evaporative loss that reduces its diameter, thus maintaining relatively constant wattage. The result is a lamp that deliv-

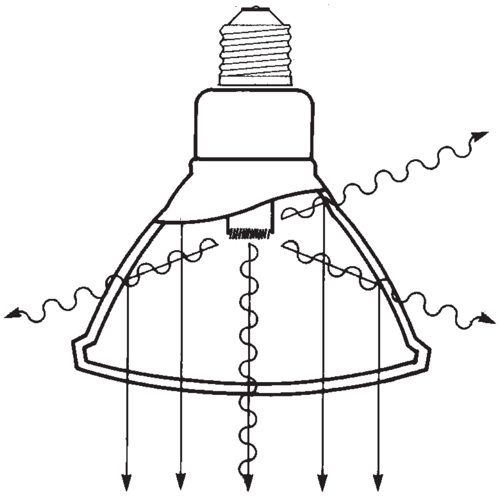


Figure 6.9 Cool-beam PAR lamp. Since the unwanted heat is transmitted from the back of the lamp, cool-beam lamps are to be used only in luminaires designed to allow the heat to escape.

ers almost its full light output throughout its life (figure 6.10).

In order for this self-cleaning cycle to occur consistently, the temperature of the lamp bulb must be a minimum of 500°C. The use of quartz rather than glass is dictated by this thermal requirement and the need for strength to resist high internal gas pressures. Although quartz is no longer the only material used for the enclosure of these lamps, the lamps are still sometimes referred to as "quartz-halogen."

The high internal pressure may cause an explosive shattering of the bulb if it develops a fault and fails. Although this is a rare occurrence, halogen lamps must be enclosed because fragments of quartz glass are hot and can cause burns or start a fire. The halogen tube is either enclosed in an outer bulb or used in a luminaire equipped with a glass cover or fine mesh screen.

The higher the operating temperature of a filament, the higher the color temperature. Therefore, halogen lamps have a higher color temperature than conventional incandescent lamps. And, greater energy in the blue region of the spectrum makes them appear "whiter." They have longer life and greater efficacy; they are also more compact, permitting the use of smaller luminaires.

Halogen lamps are available in five configurations: (1) single-ended T; (2) double-ended T; (3) integral-reflector AR, MR, and PAR; (4) modified A-lamp CP, MB, and TB; and (5) modified decorative B and F shapes.

Single-ended halogen lamps have bayonet, bipin, miniature screw, mini-candelabra ("mini-can"), twist-and-lock (TAL), or two-pin bases in sizes that range from T3 to T24 and wattages from 5 W to 10,000 W.

Double-ended halogen lamps have recessed single contact (RSC) bases, one at

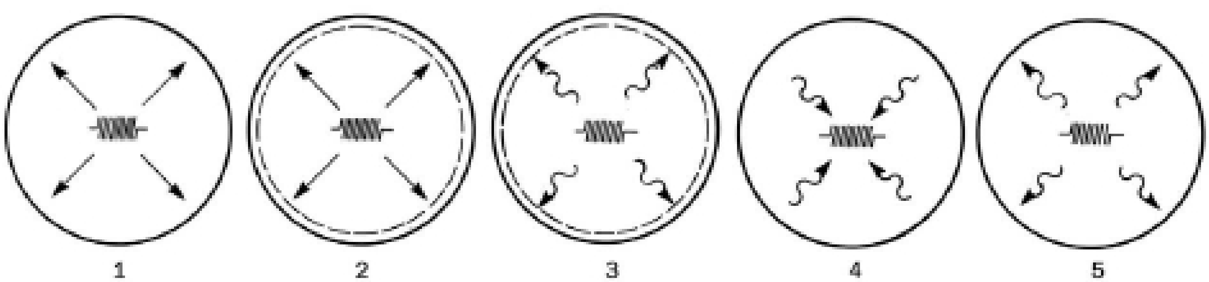


Figure 6.10 Halogen cleaning cycle.

each end of the lamp. Their bulbs are of small diameter: T2, T2½, T3, T4, T6, and T8. Wattages range from 45 W to 2,000 W.

Halogen Infrared (IR) Lamps

Of the energy radiated by standard incandescent and halogen lamps, 85 percent is invisible infrared (heat). *Infrared reflecting* (*IR*) halogen lamps have a thin, infrared-reflective coating applied to the inner filament tube that converts some of the infrared energy to visible light. The coating allows visible light to pass through the tube wall; the infrared energy is reflected back onto the lamp filament, further heating the filament and producing more visible light for the same amount of energy.

The operating temperature for the halogen cycle is maintained with less input power, resulting in increased efficacy: the efficacy of a standard 1750 lm, 100 W, A-lamp is 17.5 lm/W; conventional halogen lamps have efficacies of approximately 20 lm/W; halogen IR lamps have efficacies in excess of 30 lm/W.

LOW-VOLTAGE LAMPS

Low-voltage lamps are not of magical construction—they are simply incandescent and tungsten-halogen lamps that operate between 6 V and 75 V.

The wattage of all filament lamps is the product of the voltage delivered at the socket multiplied by the *amperes* (current) flowing through the filament. The lower the voltage of the lamp of a given wattage, the higher the amperes and the larger the diameter of the filament wire required to carry it.

The increased diameter of the filament wire of low-voltage lamps allows for a more compact filament. The more compact the filament, the more precise the beam control. The main advantage of low-voltage lamps is their precise beam control.

An increase in the diameter of a filament wire raises the temperature at which it can be operated without danger of excessive evaporation. High-wattage lamps, therefore, are more efficacious than low-wattage lamps of the same voltage and life rating. Lower-voltage lamps, because their filament wire is of greater diameter, are also more efficient than higher-voltage lamps of the same wattage; thus, a 120 V lamp (common in the United States and Canada) is more efficacious than the 250 V lamps used in much of the rest of the world.

Low-voltage reflector lamps with narrow beam-spreads are energy-saving when their concentrated distribution is used to light small objects or large objects at great distances because light is confined to the lighted object without spilling beyond it. Where wider beams are required, low-voltage lamps are often less efficient than standard lamps.

Low-voltage operation also means that the standard building current of 115 V to 125 V must be stepped down by the use of a *transformer*. Low-voltage luminaires with integral transformers are often larger, bulkier, and more expensive than line-voltage equipment.

The low-voltage lamps commonly used for architectural applications operate at 12 V. They include PAR, AR, and MR lamps. Low-voltage PAR lamps are manufactured in the same way as line-voltage PAR lamps; the shape and diameter of the lamps may differ, and the bases are always different to avoid wrong electrical connection (figure 6.11).

Many low-voltage PAR lamps are equipped with filament shields to minimize the stray light that comes directly from the filament. As a result, the lamps emit only the controlled beam from the reflector. These filament shields have the added benefit of providing glare control by preventing view of the filament.

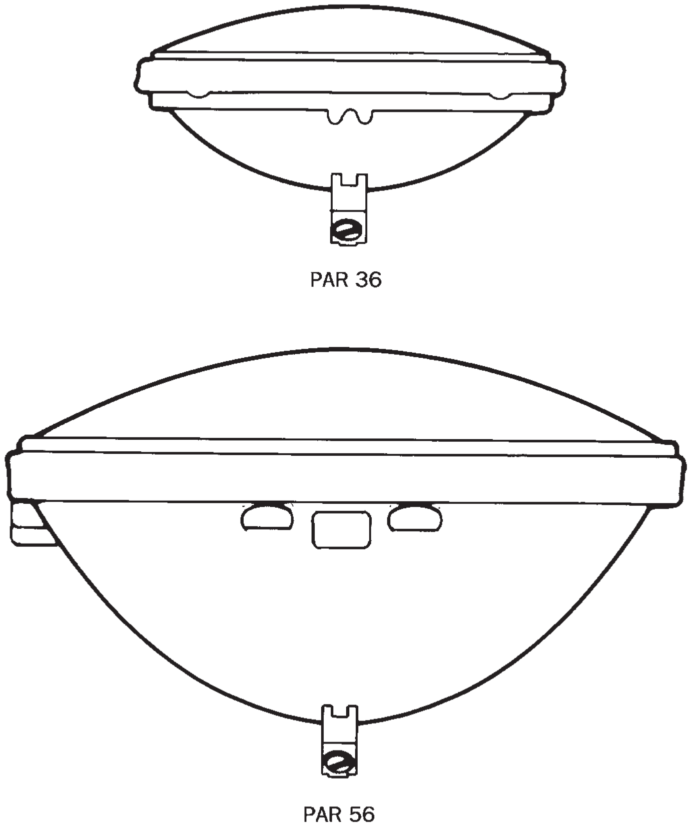


Figure 6.11 Low-voltage PAR36 and low-voltage PAR56 lamps at one-half actual size.

The *aluminum reflector* (AR) lamp consists of a prefocused axial filament lamp and faceted aluminum reflector that form an optical system. With some AR lamps the filament cap forms a grip for easy handling in addition to preventing direct glare from view. Other AR lamps have an integral diffusing glass lens to modify the beam-spread.

AR lamps are available without lenses in diameters of 70 mm and 111 mm (figure 6.12) and with lenses in diameters of 37 mm and 56 mm. The AR111 lamp is comparable to the PAR36 lamp size and base and is used interchangeably with sealed-beam PAR36 lamps. AR111 lamps also have excellently designed reflector surfaces.

With *multifaceted mirror-reflector (MR)* lamps, a small halogen lamp is attached to a mirror with a surface composed of specular facets (flood) or a smooth plane (spot) (figure 6.13). The mirror is ellipsoidal in shape; the lamp's coiled filament is placed near its focus.

This combination acts as an optical condensing system in slide projectors, removing the need for lenses to control the light pattern. By changing the shape of the mirror or relocating the light source within the reflec-

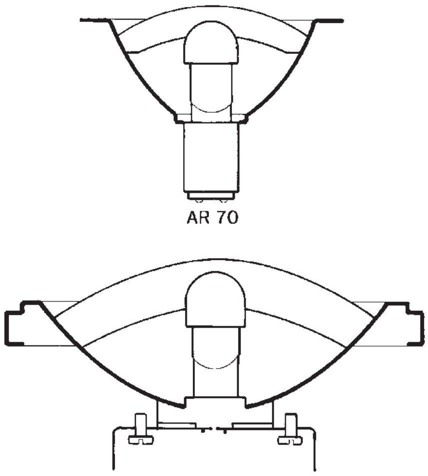


Figure 6.12 AR70 and AR111 lamps at one-half actual size.

tor, MR lamps are produced with beamspreads from 7° (very narrow spot) to 60° (wide flood).

MR lamps are available in both 1⅜ in (MR11) and 2 in (MR16) diameters with either a miniature two-pin or turn-and-lock (50 W only) base. MR11 lamps are offered in 12 W, 20 W, and 35 W versions. MR16 lamps are offered in 20 W, 35 W, 42 W, 50 W, 65 W, 71 W, and 75 W versions. MR16 IR (infrared-reflecting) lamps are available in 20 W, 35 W, 37 W, 45 W, and 50 W versions.

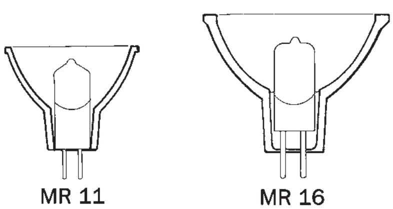


Figure 6.13 MR11 and MR16 lamps at one-half actual size.

Originally all MR11 and MR16 lamps had glass bulbs, two-pin bases, open fronts, and dichroic reflector coatings. These coatings remove two-thirds of the infrared heat from the projected beam and pass it through the back of the lamp, with the advantages described earlier for dichroic PAR38 cool-beam lamps.

The compact size of these lamps encouraged the design of compact luminaires. This often caused severe problems of heat build-up, however, because heat that is usually radiated from the front of a directional lamp now passes through the back and into the luminaire. To correct this problem, lamp manufacturers developed some MR11 and MR16 lamps with an aluminum-reflector coating that substitutes for the dichroic coating. This aluminum reflector coating also prevents "spill" light from the back of the lamp.

MR lamps are also available with a glass cover on the front of the lamp to protect against shattering of the halogen tube and, in some cases, to spread and smooth the beam. Other variations include reflectors made of aluminum instead of glass and turn-and-lock bases instead of the two-pin bases. Lamps with improved dichroic coatings provide constant color over lamp life, longer lamp life, and improved lumen maintenance.

COLORED LIGHT

Colored light is commonly described in terms of hue, saturation, and brightness. Hue is the quality that is called red or green. Saturation is the strength or depth of the color—the amount by which the light appears to differ from white. A deep red light, for example, is said to be of high saturation; pink is a red of low saturation. Brightness is the perceived quantity of light, without regard to hue or saturation.

A colored or filtered incandescent lamp produces colored light by starting with "white" light and filtering out the undesired portions of the spectrum. Yet most colored light sources, even those that appear highly saturated, are not truly monochromatic. They emit a fairly wide band of wavelengths, often including small amounts of energy in other hue regions. The less saturated the color, the greater the content of other hues.

Color Filters

The predominant method of producing colored light is the use of color *filters* with a "white" light source. The white source contains all of the colors of the spectrum; the filter absorbs the unwanted parts of the spectrum and transmits the wavelengths that make up the desired color.

Color filters are usually designed for incandescent lamps. Other types of light sources, lacking a truly continuous spectrum, are seldom used with color filters. The greatest use of colored light is in retail store windows and in theatre, television, and photographic lighting.

Gelatin filters ("gels") are thin, colored, transparent plastic sheets available in a wide variety of colors as well as multicolored and diffusing sheets. Deeper saturations are obtained by using more than one thickness. Gels have a short service life because their color fades rapidly when they are transmitting intense light and heat.

Colored plastic panels are available for use with fluorescent lamps but are unsatisfactory for use with hot incandescent filaments. Colored glass filters, which can withstand the heat of incandescent lamps, come smooth, stippled, prismatic, or split; they are highly stable.

Interference filters consist of one or more layers of ultrathin film coating on clear glass that reflect rather than absorb the unwanted wavelengths. The number and thickness of the film coatings determine the transmission (hue and saturation). Because unwanted wavelengths are not absorbed, interference filters remain cool.

Some interference filters are designed to reflect or transmit a portion of the spectrum: infrared or ultraviolet or both. Broadband interference filters are often called dichroic ("two-colored") because they transmit one color and reflect the complimentary color (figure 6.14).

It is advisable to determine the approximate spectral composition of the "white" light source before selecting a filter. If the desired wavelengths are not present in the original source, the filter will be ineffective. An extreme example is a red lamp with a green filter, which will transmit no visible light.

Colored Lamps

Incandescent colored sign and decorative lamps have outside ceramic enamels, sprayed finishes, or dip coatings applied to clear bulbs to obtain colored light by the subtractive method: by absorbing the light of those colors that are undesirable.

Transparent ceramic enamels are used to coat clear glass bulbs; the finely ground colored glass is fired into the bulb to fuse the coating into a hard, permanent finish. The coating is applied before the bulbs are made into lamps. This makes these lamps resistant to scuffing, chipping, and weather, but they are less transparent than lamps with lacquers or plastic coatings.

Sprayed finishes, usually shellacs or silicones, are applied to the completed lamp. Although these sprayed coatings have good adhesion, they lack the hardness of the ceramic enamels and have less resistance to scratches or scuffing. Sprayed lacquers are highly transparent and therefore often used when the sparkle of a visible filament is desired.

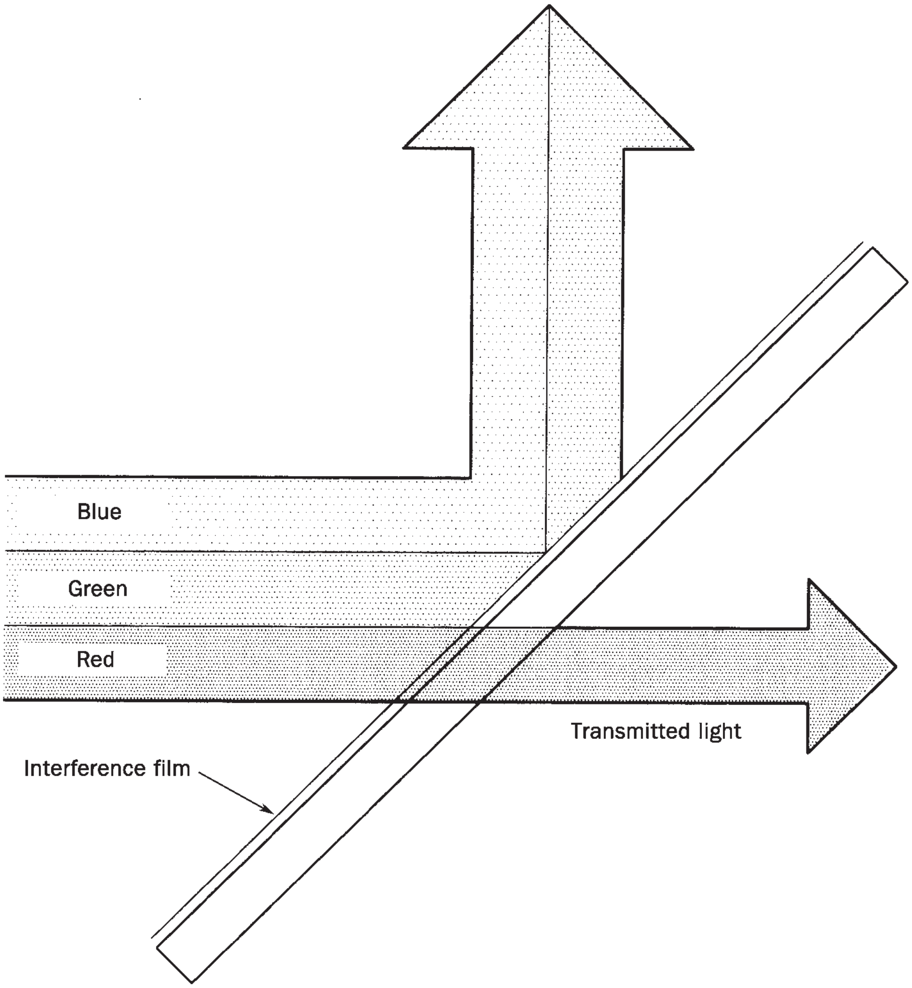


Figure 6.14 Interference (dichroic) filter.

Dip coatings of transparent colors that are given an overcoat of acrylic are an improvement over the sprayed lacquers; they yield a similar result with a higher resistance to abrasion and weather. These plastic-coated lamps offer more sparkle, greater brightness, and higher saturation for any given color.

Colored 50R20, 75R30, and 150R40 lamps are manufactured with fired enamel finishes. Colored 100PAR38 lamps have a coating of dye-impregnated silicone plastic, similar to the plastic-coated sign lamps.

Colored 150PAR38 lamps have dichroic interference filters that are vacuum-deposited on the inside of the cover lens. The filter produces its specific color by transmitting only the desired wavelengths of light, with minimal heat absorption; light of other wavelengths is reflected back into the lamp. It is often more efficient than passing light through color-absorbing materials, and it produces a more brilliant color than absorption methods.

Discharge Lamps 7

In electric discharge lamps, light is produced by the passage of an electric current through a vapor or gas, rather than through a tungsten wire as in incandescent lamps.

The light production by *discharge* sources is more efficient than the electric heating method used in filament lamps. Discharge lamps used in architectural lighting are more efficacious and have a longer life. See table 4 in the Appendix.

FLUORESCENT LAMPS

A *fluorescent* lamp is a low-pressure mercury arc discharge source. Its operation relies on an electrical arc passing between two cathodes, one at either end of a glass tube. Fluorescent lamps require a *ballast* to provide the proper starting voltage and regulate the lamp operating current.

When the voltage difference between the two cathodes is sufficient to strike an arc, an electric current passes through mercury vapor within the bulb. As the arc current passes through the vapor, it causes changes in the energy levels of electrons in the individual mercury ions. As the electrons change levels, they release several wavelengths of visible and ultraviolet energy. This radiation strikes the tube wall, where it causes phosphor material to fluoresce (become luminous) and emit light (figure 7.1).

Because light emanates from the phosphor, light from a fluorescent lamp is emitted from the surface of the bulb; the entire tube is the actual light source. Average luminance of the lamp is comparatively low because light is generated from a large area. See table 5 in the Appendix.

The selection of phosphors and additives determines the kind of light that is produced: ultraviolet light, colored light, or the more commonly numerous variations of "white" light.

Although operating principles are the same for all fluorescent lamps, two kinds of cathode exist: hot-cathode and cold-cathode. (These names are misleading, however, because the cold-cathode type dissipates more heat than the hot-cathode kind.)

Cold-Cathode

The *cold-cathode* lamp is a thimble-shaped cylinder of soft iron, sometimes coated with emissive materials (figure 7.2). This large-area source of electrons has an extremely long life. Voltage drop at the cathode is higher than with a hot cathode; therefore, the watt-

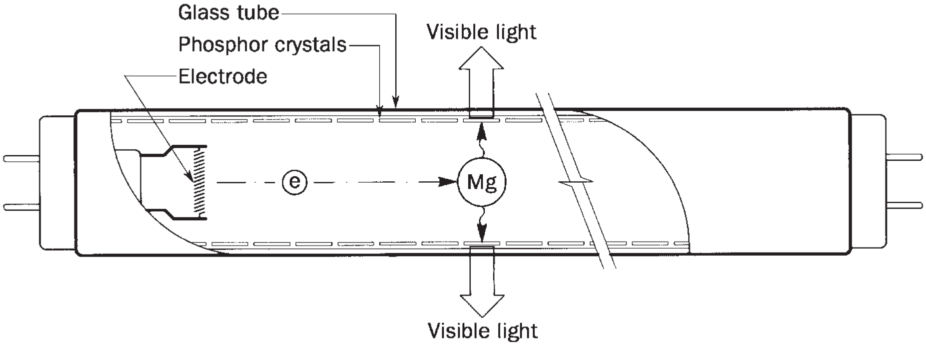


Figure 7.1 The fluorescent (hot-cathode) lamp consists of a glass tube, internally coated with phosphors that convert ultraviolet energy into light; cathodes supported by a glass structure and sealed at the ends of the tube; a filling gas to aid starting and operation—usually a combination of krypton, argon, and neon; a small amount of mercury, which vaporizes during lamp operation; and a base cemented on each end of the tube to connect the lamp to the lighting circuit.

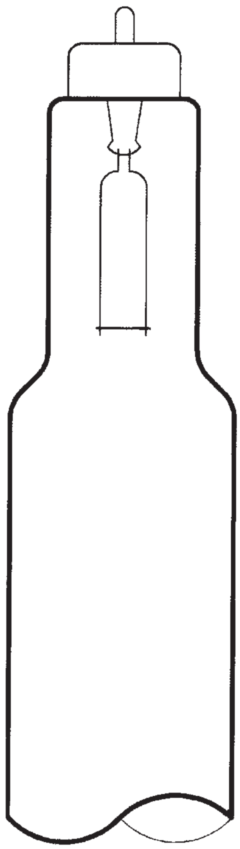


Figure 7.2 Cold-cathode lamp.

age loss is greater, more heat is developed, and lamp efficacy is lower.

Neon is a particular kind of small-diameter, cold-cathode lamp; it is easily bent to form signs and artworks. The operating principle is related to that of other cold-cathode lamps, but light is produced by excitation of the gas itself without the help of phosphors. All cold-cathode lamps provide instant starting and are easily dimmed.

Although lower in efficacy and output, cold-cathode lamps have a longer life. They are used for decorative applications and in places where inaccessibility makes lamp replacement difficult. Cold-cathode lamps are less frequently used than the hot-cathode kind.

Hot-Cathode

Hot-cathode lamps are used for virtually all fluorescent lighting. The cathode is a coiled tungsten filament at each end of the bulb impregnated with electron-emissive materials. Hot-cathode lamps are operated at a higher light output per unit length and with a higher overall efficacy than cold-cathode lamps, resulting in a lower cost for equal illuminance.

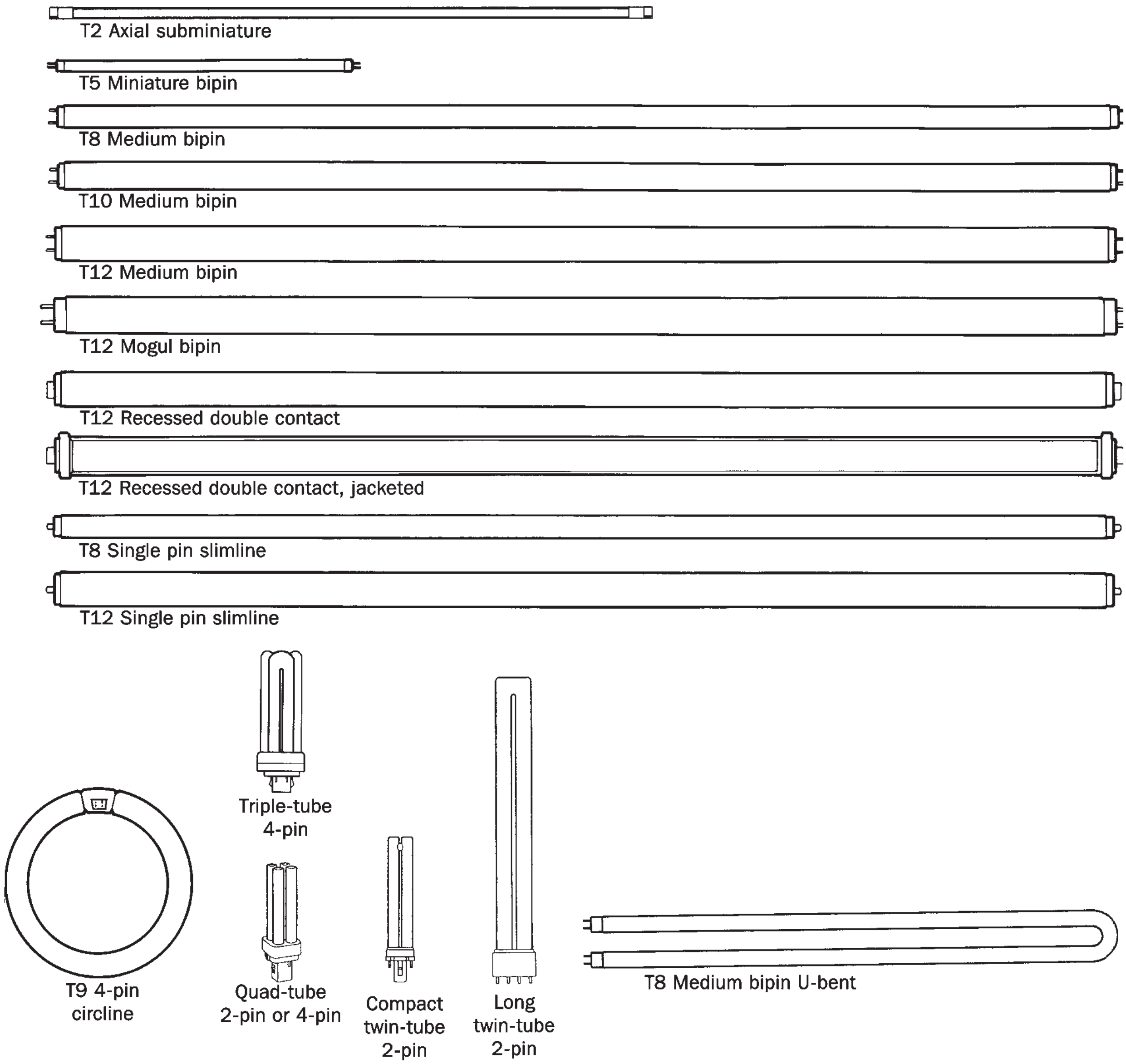


Figure 7.3 Fluorescent lamp shapes and sizes at one-eighth actual size.

The superior efficacy and greater light output make the hot-cathode ("fluorescent") lamp more suitable in almost all lighting applications; hot cathode lamps are the principal light source for lighting building interiors. Fluorescent lamps are usually identified by an "F" followed by wattage, shape, bulb diameter in eighths of an inch, and color (phosphor kind and correlated color temperature). For example, F32T8/RE830 is a 32 W, 1-in-diameter, fluorescent lamp with rare-earth phosphors and a correlated color temperature of 3000 K (figure 7.3).

Lamp-ballast circuits

Fluorescent lamps require a ballast to regulate the electric current through the lamp. Three kinds of fluorescent lamp-ballast circuits are made: preheat, instant-start, and rapid-start.

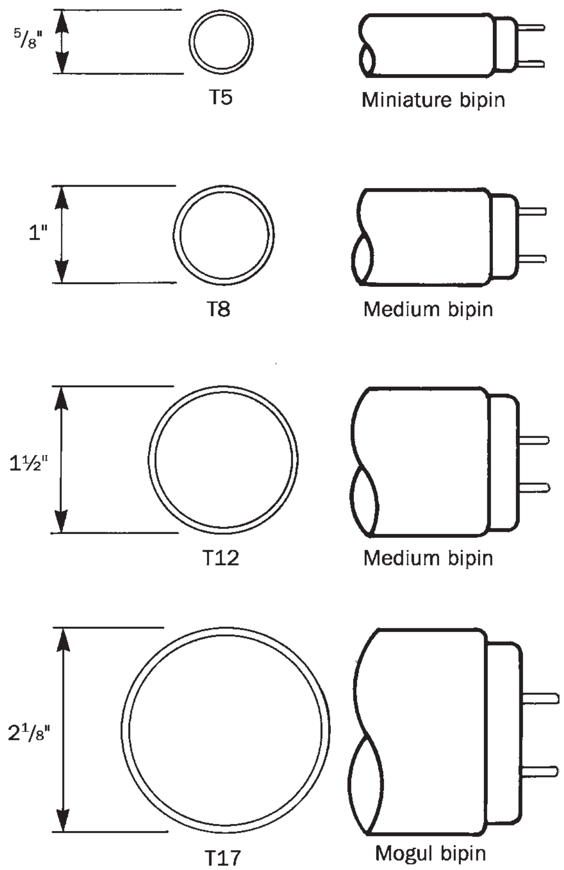


Figure 7.4 Preheat fluorescent lamp diameters and bases at one-half actual size.

The earliest fluorescent lamps were of the *preheat* kind (figure 7.4). Preheat lamps have cathodes that must be heated electrically in order to make them emit electrons and thus ionize the gas in the tube, making it more conductive and raising the voltage necessary to strike the arc. The current heats the cathodes; because this occurs before the arc strikes, it is said to preheat them.

The preheating process takes a few seconds. It is usually controlled by an automatic *starter*, which applies current to the cathodes of the lamp for a sufficient length of time to heat them; it then automatically shuts off, causing the voltage to be applied between the cathodes and striking the arc.

The preheating is sometimes accomplished by holding down a manual start

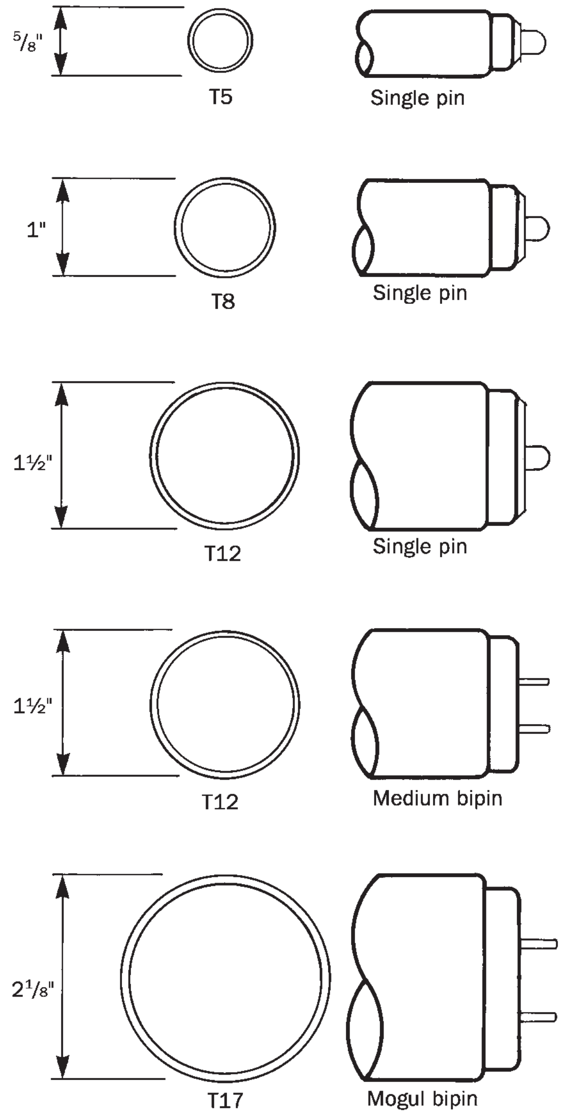


Figure 7.5 Instant-start lamp diameters and bases at one-half actual size.

button, as with some fluorescent desk luminaires. The button is held down for a few seconds while the cathodes heat; when the button is released, the arc strikes. Whether started manually or automatically, once the lamp is in operation, the arc maintains the cathode temperature.

Instant-start lamps are designed to operate without a starter (figure 7.5). This simplifies the lighting system and its maintenance. The ballast provides sufficient voltage

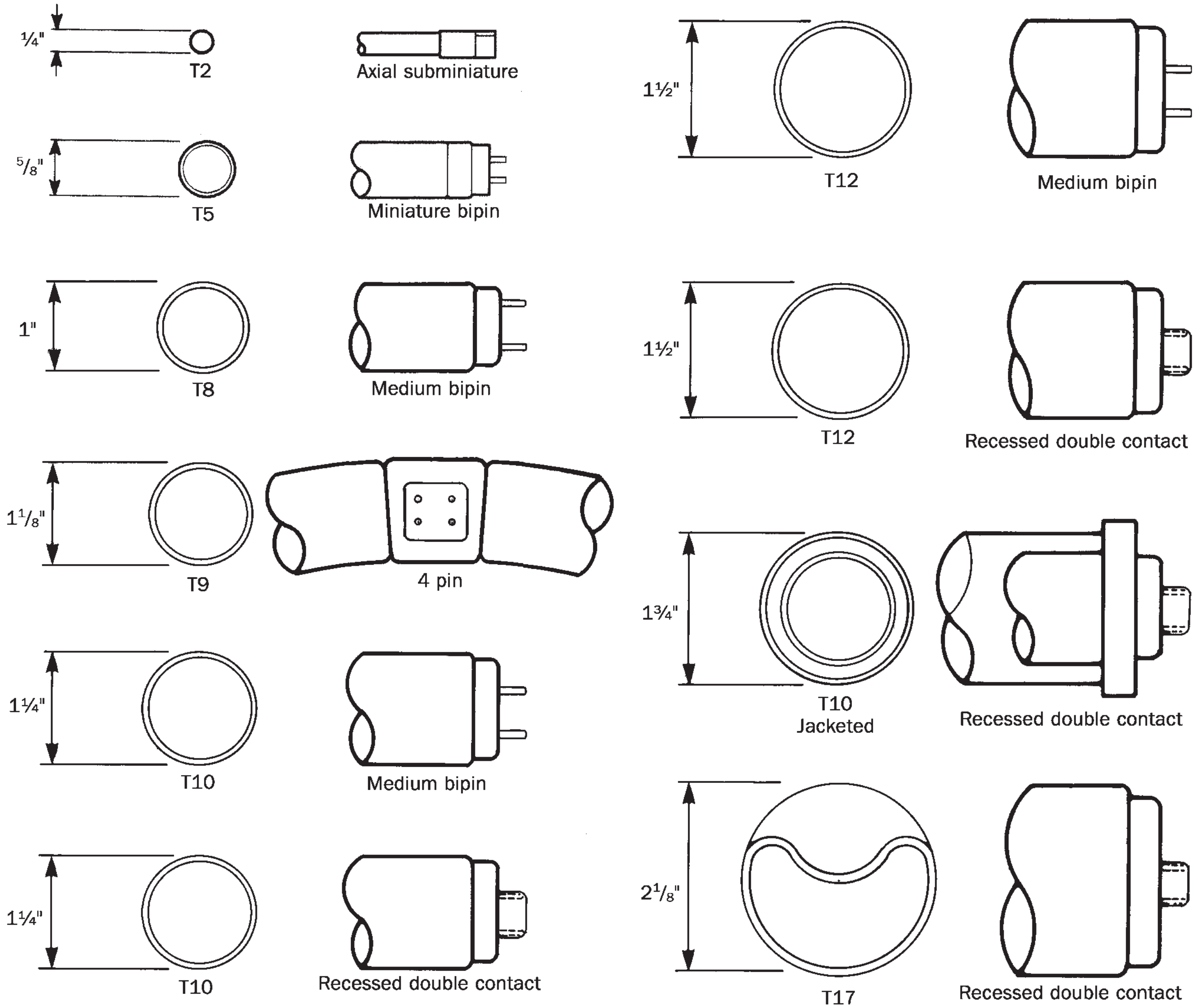


Figure 7.6 Rapid-start lamp diameters and bases at one-half actual size.

to strike the arc instantly. This is a violent action that requires cathodes able to withstand the jolt of instant starting.

Because preheating is unnecessary with instant-start lamps, only one external contact is located on each end of the lamp. Some instant-start lamps have bipin bases; lamps with single-pin bases are called *slimline* lamps. In these lamps, the pins are connected inside the base.

Slimline lamps can be operated at more than one current and wattage. For this reason, they are identified by length rather than lamp wattage. The number following the "F" in the designation is the nominal lamp length. For example, F96T12/RE830 is a 96 in (8 ft), 1½-in-diameter, slimline lamp with rare-earth phosphors and a correlated color temperature of 3000 K.

Rapid-start lamps combine the features of the preheat and instant-start circuits (figure 7.6). Starters are unnecessary. The ballasts have separate windings that heat the cathodes continuously; the lamps start almost instantly after being switched on, but less voltage is required for starting than with instant start lamps of comparable length. Rapid-start ballasts are less expensive, smaller, and have lower power loss than instant-start ballasts.

Rapid-start lamps are sometimes operated with instant-start ballasts. The instant-start ballasts provide higher voltage to start the lamps, but they do not supply current to the cathodes during lamp operation. The savings is approximately 2 to 3 watts per lamp.

Because the cathodes of rapid-start lamps are heated continuously during operation, these are the only fluorescent lamps that can be dimmed or flashed.

Trigger-start ballasts permit the operation of preheat fluorescent lamps up to 32 W without the use of starters. This circuit was developed prior to the rapid-start circuit and is similar in operation: it provides continuous heating of the cathodes, and starters are unnecessary. The lamps are made with bipin bases to permit the flow of current through the cathode filaments before the lamp starts.

For reliable starting, rapid-start and trigger-start lamps must be mounted within 1 in of a 1-in-wide grounded strip of metal, or within ½ in of a ½-in-wide grounded strip of metal, running the full length of the lamp. This is usually provided by a wiring channel or reflector in the luminaire housing.

T8 and T5 lamps

Good color-rendering fluorescent lamps require the use of rare-earth phosphors, which are more expensive than standard phosphors. For this reason, smaller-diameter *T8* and *T5* lamps are produced. (The T8 [1-in-diameter] bulb uses only two-thirds of the phosphor quantity required by the *T12* [1½-in-diameter] bulb, for example; it is therefore less expensive to produce.) The smaller diameter also gets the phosphors closer to the arc, increasing the efficiency of light generation.

In addition to better color rendering, the rare-earth phosphors provide a substantial increase in lighting efficiency. System efficacies up to 80 lumens per watt for T8 lamps on magnetic ballasts and up to 105 lumens per watt for T8 lamps on electronic ballasts compare with 65 to 75 lumens per watt with T12 lamps and ordinary phosphors. Due to their higher efficacies, T8 lamp-ballast systems have replaced conventional T12 lamps in many applications.

(Lamp manufacturers report *lamp efficacy:* lumens per watt when the lamp is operated under reference conditions. *System efficacy* is lumens generated by the lamp when operated by a given ballast divided by the input watts to the ballast.)

As tube diameter decreases in size, luminance is increased, requiring better methods of shielding the source. The smaller bulb diameter also increases the luminaire optical efficiency, however, yielding smaller luminaires with the potential for improved light-distribution patterns.

For T8 lamps, three kinds of rare-earth phosphors are available: RE-70, RE-80, and RE-90. Color temperature is varied according to the relative balance among the phosphors. RE-70 and RE-80 lamps have three narrow-emission phosphors that produce three "peaks" of visible energy: a blue, a green, and a red (see color plates 19, 20, and 21). RE-70 lamps contain a coat of conventional phosphors and a thin coat of the rare-earth triphosphors to produce a CRI of 70 to 79. RE-80 lamps contain a thick coat of the rare-earth triphosphors, increasing CRI to 80 to 89 with full light output and lumen maintenance.

RE-90 lamps do not use the three narrow-emission phosphors of the other two rare-earth lamps. These quad-phosphor lamps contain four wider-emission phosphors that produce CRIs of 95 at 3000 K and 98 at 5000 K (see color plates 22 and 23).

In addition to the four rare-earth phosphors, the RE-90 3000 K lamp has filters to reduce the quantity of blue light caused by mercury radiation, balancing the color. Light output of RE-90 lamps is reduced by one-third, but this is often imperceptible because of the vivid and accurate colors, which improve contrast and portray tones that are otherwise grayed with lamps of lower CRIs.

T5 (5⁄8-in-diameter) fluorescent lamps are only manufactured in metric lengths and with a miniature bipin base, and are designed to operate solely on electronic ballasts. Their smaller diameter provides even better optical control than T8 lamps. Additionally, T5 lamps produce optimum light output at an ambient temperature of 95ºF (35ºC) rather than the more typical 77ºF (25ºC) of other fluorescent lamps, allowing for the design of more compact luminaires that do not require added size to dissipate heat.

T5 lamps are also available in high-output versions providing almost twice the light output per length as their standard T5 counterparts. At the present time, all T5 lamps are available only with RE-80 phosphors.

Variations

Energy-saving or reduced-wattage lamps are interchangeable with standard lamps; they consume less power and deliver less light. Input wattage is reduced by 12 to 15 percent; lumen output is reduced by 10 to 20 percent. Energy-saving lamps are more sensitive to low temperatures than standard lamps: minimum starting temperature is 60°F, as opposed to 50°F for standard lamps.

T8 and T12 *U-bent* fluorescent lamps are regular 4-ft lamps bent into a “U” shape. This configuration allows two or three 4-ft lamps to be used in a 2-ft-square luminaire, with the further advantage of wiring and lampholders being conveniently located at one end of the luminaire.

T8 U-bent lamps are available in 1 5⁄8-in and 6-in leg spacing, with the 6-in leg spacing more common. T12 U-bent lamps are available in 3 5⁄8-in and 6-in leg spacing, with the 6-in leg spacing again more common.

Circular “circline” lamps are T9 (1 1⁄8-in-diameter) tubes bent in a circle with the two ends adjacent to each other and a single, four-pin connector base. They are available in 6½-, 8¼-, 12-, and 16-in outside diameters. Circline lamps are of the rapid-start design but operate equally well on preheat or trigger-start ballasts.

Circular T5 lamps are also available, in 9- and 12-in outside diameters. These lamps have a single base with a two-pin connector.

High-output (*HO*) T12 rapid-start lamps operate at 800 milliamperes (mA), compared with 425 mA for most standard rapid-start lamps. They produce about 45 percent more light than slimline lamps of corresponding physical size as a result of drawing considerably more current than the standard lamps.

High-output lamps are identified by lamp length, bulb diameter, color, and the letters *HO*. For example, F96T12/RE830/HO is an 8-ft, 1½-in-diameter, rare-earth, 3000 K, high-output lamp. HO lamps are available in lengths from 18 to 96 in, with a variety of phosphors and color temperatures, and in reduced-wattage, energy-saving versions.

Very-high output (VHO) T12 lamps also operate on the rapid-start principle at 1500 mA. They produce up to twice as much light as standard lamps of equal length, while using approximately three times more power. These are the most powerful fluorescent lamps available.

Reflector and *aperture* lamps contain an internal reflector on part of the inner surface of the tube to provide built-in directional light control. The un-reflectorized portion of the

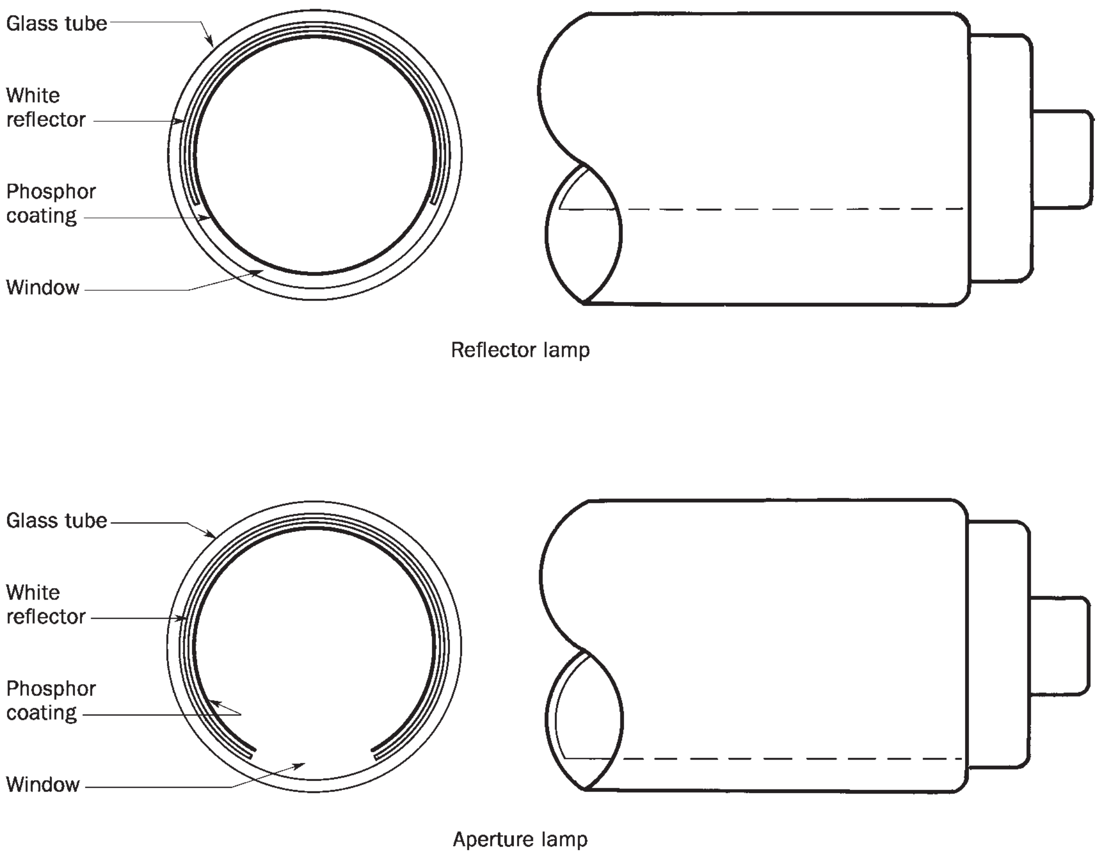


Figure 7.7 Reflector and aperture fluorescent lamps at one-half actual size.

tube is called the *window.* Intensity of light emitted through the window is significantly increased; total light output is reduced, however. Except in special applications, regular lamps in efficient luminaires perform better (figure 7.7).

Compact fluorescent lamps

Compact fluorescent lamps provide high efficacy, a CRI of 82, and 10,000- to 20,000-hr lives in a single-ended, multi-tube fluorescent lamp (figure 7.8). They operate in the preheat and rapid-start circuit modes; many have a starter built into the lamp base.

Compact fluorescent lamps have significantly higher lumen output per unit length than conventional small fluorescent lamps. This is the result of high phosphor loading, which is necessary because of their small diameter and sharp-cornered, multi-tube bulb shape. As with all fluorescent lamps, compact ones require a ballast in order to start and operate properly.

The compact lamps use the same high-color-rendering rare-earth phosphors as the T5 and T8 lamps mentioned earlier. Color temperature varies according to the relative balance among the phosphors. The 2700 K

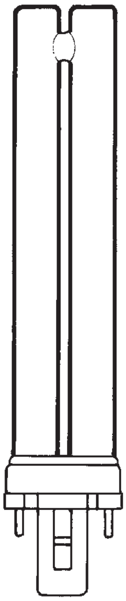


Figure 7.8 Twin-tube compact fluorescent lamp at one-half actual size.

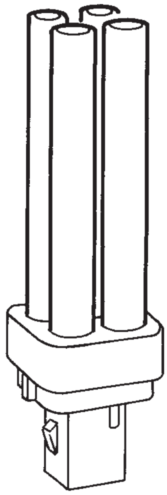


Figure 7.9 Quad-tube compact fluorescent lamp at one-half actual size.

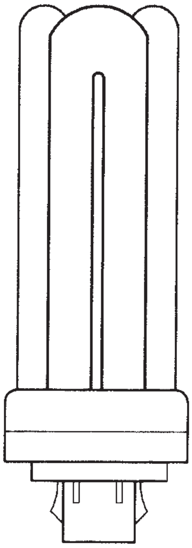


Figure 7.10 Triple-tube compact fluorescent lamp at one-half actual size.

color temperature is often used to simulate the color of standard incandescent lamps; 3000 K is compatible with tungsten-halogen and linear, straight-tube 3000 K fluorescent lamps; 3500 K and 4100 K are compatible with straight-tube 3500 K and 4100 K fluorescent lamps, respectively.

There are six families of compact fluorescent lamps:

1. T4 (½-in-diameter) *twin-tube* preheat lamps have starter devices in the two-pin plug base of the lamp. These lamps operate on inexpensive reactor ballasts and are available from 5 W to 13 W (figure 7.8).

2. T4 or T5 (⅝-in-diameter) *quad-tube* preheat lamps have two-pin plug bases and integral starters; they are available from 13 W to 26 W (figure 7.9). Some of these lamps use reactor ballasts; others require autotransformer/reactor ballasts. Designed to be a more compact, higher lumen output variation of the twin-tube kind, they provide a substantial increase in light output compared to twin-tube lamps.

3. T4 *quad-tube* electronic lamps are similar to the quad-tube preheat lamps, except that they have four-pin plug bases and no integral starters; they are available from 13 W to 26 W (figure 7.9). Designed for operation with electronic rapid-start ballasts, they also operate on preheat circuits. These lamps can be dimmed with an electronic dimming ballast.

4. T4 *triple-tube* rapid-start/preheat lamps have four-pin plug bases without starters; they are available from 18 W to 70 W (figure 7.10). Designed to deliver high

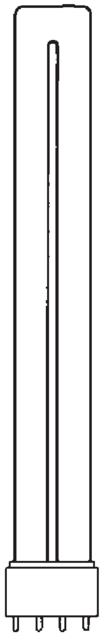


Figure 7.11 "Long" compact fluorescent lamp at one-quarter actual size.

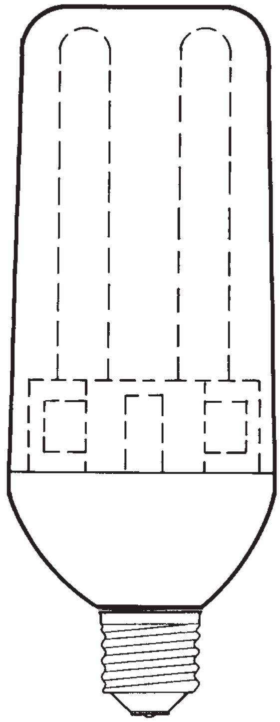


Figure 7.12 Non-modular, self-ballasted, compact fluorescent lamp.

lumen output from a small package, they are frequently used in recessed luminaires that resemble familiar incandescent downlights and wall-washers. These lamps can be dimmed with an electronic dimming ballast.

5. T5 twin-tube "*long*" rapid-start/preheat lamps have a four-pin in-line base without a starter; they are available from 18 W to 80 W (figure 7.11). These are higher-output lamps, designed to provide the lumen output of conventional fluorescent lamps in smaller packages. These lamps can be dimmed with an electronic dimming ballast.

6. *Self-ballasted* compact fluorescent lamps are designed to directly replace incandescent lamps, providing savings in energy and maintenance. They are a complete system, containing a double-folded compact fluorescent lamp, an instant-start electronic ballast, an outer diffuser, and a medium screw base (figure 7.12). They are available in two kinds: modular (replaceable lamp) and non-modular. The lamps consume one-fourth to one-third as much energy as their incandescent counterparts and last up to ten times longer. These compact fluorescents with medium screw bases are less efficacious than other compact

fluorescent lamps, but offer a means of easily increasing the efficiency of an incandescent luminaire.

Light output

During the first one hundred hours of burning a new fluorescent lamp, the initial lumen output drops by about 5 percent; lumen reduction thereafter is less rapid. Consequently, the published “initial lumens” for fluorescent lamps is the value obtained after the first hundred hours of burning.

The depreciation in light output during the life of the lamp is approximately 15 percent of the initial lumens. This is the result of the gradual deterioration of the phosphor powders and the evaporation of electron-emissive material from the cathodes, which causes blackening of the glass bulb adjacent to the cathodes.

The end of life is reached when the emission material on either cathode is depleted. Failed preheat lamps flash on and off or extinguish; instant-start and rapid-start lamps extinguish, flicker, or operate at reduced luminance.

Lamp life

Lamp life varies with the different kinds of fluorescent lamps. Rated average life of fluorescent lamps is based on the average life of a large representative group of lamps tested in a laboratory under controlled conditions; it is expressed in “burning hours.” Preheat lamps have rated average lives of 7,500 to 9,000 hrs, slimline lamps 7,500 to 12,000 hrs, rapid-start lamps 14,000 to 24,000 hrs, high-output lamps 9,000 to 12,000 hrs, and very-high-output lamps 10,000 to 12,000 hrs.

The starting of all fluorescent lamps is affected by the ambient temperature. Low temperatures require higher voltages for reliable starting. The majority of ballasts provide voltages that start standard lamps down to 50°F. Ballasts are available for certain kinds of lamps that can start lamps down to 0°F and down to –20°F.

Because each start further depletes the tungsten cathodes, the average life of fluorescent lamps is affected by the number of lamp starts. Frequent starting shortens life; life is lengthened as the number of burning hours per start is increased. Published lamp-life ratings are based on an arbitrarily assigned three hours of burning per start. The life of cold-cathode lamps is unaffected by the number of starts.

EPACT

The U.S. Energy Policy Act of 1992 (EPACT) established minimum efficacy standards for certain kinds of fluorescent lamps. The efficacy standards are a combination of minimum average lamp efficacy, measured in lumens per watt, and minimum color rendering index (CRI). No full-wattage F40, F40/U, F96, or F96/HO lamps can be manufactured or imported unless the lamp has a CRI of 69 or higher and meets the minimum-efficacy requirement.

Full-wattage CW, D, W, WW, and WWX lamps are now unavailable; energy-saving D and WWX lamps are unavailable. CW, D, LW, W, WW, and WWX F96T12 and F96T12/HO lamps have been prohibited from manufacture or sale in the United States since 30 April 1994. CW, D, LW, W, WW, and WWX F40T12 and F40T12/U lamps have been prohibited from manufacture or sale in the United States since 31 October 1995. See table 3 in the Appendix.

Lamps with a CRI of 82 or higher are exempt from these efficacy standards. In addition, aperture, cold-temperature, colored, impact-resistant, plant growth, reflector, and ultraviolet lamps are exempt from the standards.

Until 1992, most fluorescent lamps used for architectural lighting in the United

States were T12 bulbs with less expensive phosphors and poorer color rendering. The combination of high efficacy and good color rendering has made the T8 lamp the current standard.

Colored Lamps

Colored fluorescent lamps emit only a particular portion of the spectrum; the color is determined by the selection of the phosphors used. Different mixtures of phosphor composition produce different colors of light.

In a few cases, additional filtering is required to absorb mercury radiations that will otherwise desaturate the color. For red and deep blue lamps, a filter coating is applied to the outside bulb wall.

The gold fluorescent lamp achieves its color by subtraction, because no phosphors emit mainly yellow light. A yellow filter coating on the inside of the tube absorbs the unwanted wavelengths from a warm-white phosphor. Whenever subtractive filtering is used, luminous efficacy is reduced.

Black light fluorescent lamps use a special phosphor that emits primarily near-ultraviolet energy, plus a small amount of visible blue light.

Colored fluorescent lamps vary widely in lumen output. For example, twenty-five red lamps are required to equal the lumen output of one green lamp. See table 6 in the Appendix.

Different colors of light have different degrees of effectiveness in attracting attention; this is independent of brightness intensity. See table 8 in the Appendix.

Flicker and Stroboscopic Effect

The mercury arc in a fluorescent lamp operated on a 60 Hz alternating current goes on and off 120 times per second. The light from the lamp remains visible because the phosphors have some phosphorescent or "carryover" action: they emit a reduced quantity of light for a short period of time after the arc is extinguished.

The cyclic variation in light output is known as *flicker*. With 60 Hz operation, the flicker rate over the length of the lamp is 120 cycles per second. At the ends of the lamp each alternate flash is relatively weak, occurring at a rate of 60 flashes per second.

The 120-cycle flicker is too fast to be visible. The 60-cycle flicker can be detected, but only by the peripheral vision of the retina. For this reason, lamp flicker is seldom noticed except when seeing the ends of lamps out of the corner of the eye.

When rapidly moving objects are observed under discharge lighting systems, blurred "ghost" images are sometimes observed. This is known as *stroboscopic effect.* Because of this phenomenon, an object moving at a uniform speed will appear to move in jerks. Under extreme conditions, a rotating object will seem to be standing still or even rotating in reverse direction depending on its speed of rotation and its configuration.

Stroboscopic effect rarely causes difficulty because modern phosphors have relatively long carryover periods. If a problem occurs, operating multiple ballasts on all three phases of a three-phase circuit will reduce stroboscopic effect because only one-third of the lamps operate at reduced output at a given time.

HIGH-INTENSITY DISCHARGE (HID) LAMPS

The term "high-intensity discharge" applies to arc-discharge sources with a high power density. In HID lamps, light is produced by passing an electric current through a gas or vapor under high pressure, as contrasted to the low pressure in fluorescent or low-pressure sodium lamps. HID lamps used for illumination belong to three principal families:

(1) mercury vapor, (2) metal halide, and (3) high-pressure sodium lamps.

HID lamps consist of an arc tube enclosing two electrodes and one or more metals that are vaporized and ionized to conduct current in an electric arc from one electrode to the other. When a lamp is energized, an electric field is established between the starting electrode and the main electrode, causing individual particles of the starting gas to become electrically charged (figure 7.13). With most HID lamps, the arc tube is enclosed in an outer glass bulb.

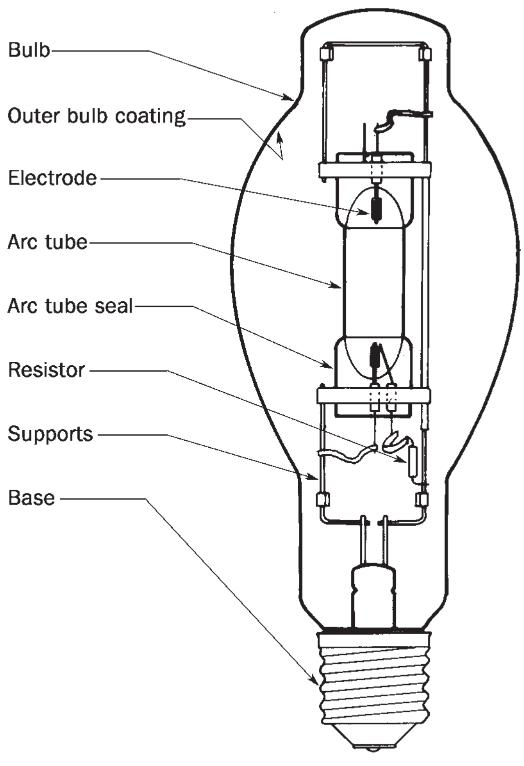


Figure 7.13 Typical high-intensity discharge lamp. With all HID lamps, the light-producing element is the arc tube; it contains metallic vapors, gases, and the electrodes at the ends of the arc tube, where the arc originates and terminates. The base connects the lamp mechanically and electrically to the luminaire.

The electrons that comprise the current stream, or arc discharge, are accelerated to tremendous speeds. When they collide with the atoms of the gas or vapor, they temporarily alter the atomic structure, and light results from the energy given off in the form of radiation as the atoms return to their normal state. The lamp warm-up process takes three to seven minutes, depending on ambient temperature conditions.

Each kind of HID lamp is unique. With *mercury vapor* lamps, light is produced by an electric discharge through mercury vapor. The electrodes are made of tungsten, in which an emission material is embedded within the turns of an inner tungsten coil protected by an outer tungsten coil. The electrodes are heated to the proper electron-emissive temperature by bombardment energy received from the arc. After the arc strikes, its heat begins to vaporize the mercury, which results in poor color quality of a greenish hue: 15 to 20 CRI (color plate 27). The addition of phosphor coatings on the inside of the bulb improves color rendering: 45 to 50 CRI (color plate 28).

In *metal halide* lamps, the electric discharge is through the combined vapors of mercury and metal halides, which are introduced into the arc tube as compound iodides. When the lamp attains its full operating temperature, the metal halides in the arc tube are partially vaporized and the metals radiate their spectrum. The metal halides radiate a wider spectrum than the mercury lamp, yielding greater efficacies and better color rendering: 65 CRI (color plate 29). The addition of phosphor coatings on the inside of the bulb provides diffusion and some additional color improvement: 70 CRI (color plate 30).

Pulse-start metal halide lamps use an arc tube with substantially higher fill pressure than standard metal halide lamps. This reduces tungsten evaporation from the electrodes, which lessens the darkening of the arc tube. As a result, pulse-start lamps provide better lumen maintenance, longer lamp life, and improved color stability compared with standard metal halide lamps.

With *high-pressure sodium (HPS)* lamps, the electric discharge is through combined vapors of mercury and sodium, with the latter dominating. This produces the orange-tinted color familiar to us in street lighting: 21 to 22 CRI (color plate 24). In HPS lamps, the inner arc tube is constructed of polycrystalline alumina (PCA), a ceramic material that is resistant to sodium attack at high temperatures and has a high melting point. By further increasing the gas pressure inside the lamp, *white high-pressure sodium* lamps produce incandescent-like color at 2700 K with good color-rendering properties and a CRI of 85 (color plate 25).

Ceramic metal halide lamps combine the ceramic arc tube technology of high-pressure sodium lamps with existing metal halide chemistry. Instead of the quartz arc tube used in conventional metal halide lamps, ceramic metal halide lamps have an arc tube made of polycrystalline alumina (PCA). PCA permits the lamp to operate at higher internal temperatures, increasing color rendering, output, and efficacy. PCA resists interaction with the chemicals inside the tube, which stabilizes the chemical mix over the life of the lamp, improving color consistency and lumen maintenance. The PCA tube is smaller than quartz tubes, which prevents the chemical mix from dispersing and further improves color consistency.

Many high-color-rendering HID lamps have shorter lives and produce lower light output than standard HID lamps, but their superior color makes them the best choice for areas inhabited by people. White high-pressure sodium lamps offer 10,000-hr lives and a CRI of 85, and some have prefocus bases to provide precise location of the source in optical systems. Ceramic metal halide lamps offer 6,000- to 15,000-hr lives and CRIs of 81 to 96; some have bipin, recessed single-contact, or mogul bipost bases to ensure accurate alignment of the light source with the optical system of the luminaire.

Bulb shapes

HID bulbs are produced in several incandescent bulb shapes. In addition, four shapes have been specially designed for HID service: B, BT, E, and ED. Bulb shapes (figure 7.14) include

A	*A*rbitrary
B	*B*ulged
BT	*B*ulged-*t*ubular
E	*E*lliptical
ED	*E*lliptical-*d*impled
PAR	*P*arabolic *a*luminized *r*eflector
R	*R*eflector
T	*T*ubular

The descriptive abbreviation of an HID lamp includes a multi-letter code that identifies the lamp kind or trade name and a number that identifies the lamp's wattage, followed by suffixes that may include lamp shape, a number that represents the maximum diameter of the bulb in eighths of an inch, outer bulb finish, operating position, base, and color. The American National Standards Institute (ANSI) code for description of HID lamps provides suggested standardized nomenclature among manufacturers.

Example: CMH100/C/U/MED/830

CMH	*c*eramic *m*etal *h*alide lamp, also CDM (for *c*eramic *d*ischarge *m*etal halide) and MHC for *m*etal *h*alide *c*eramic)

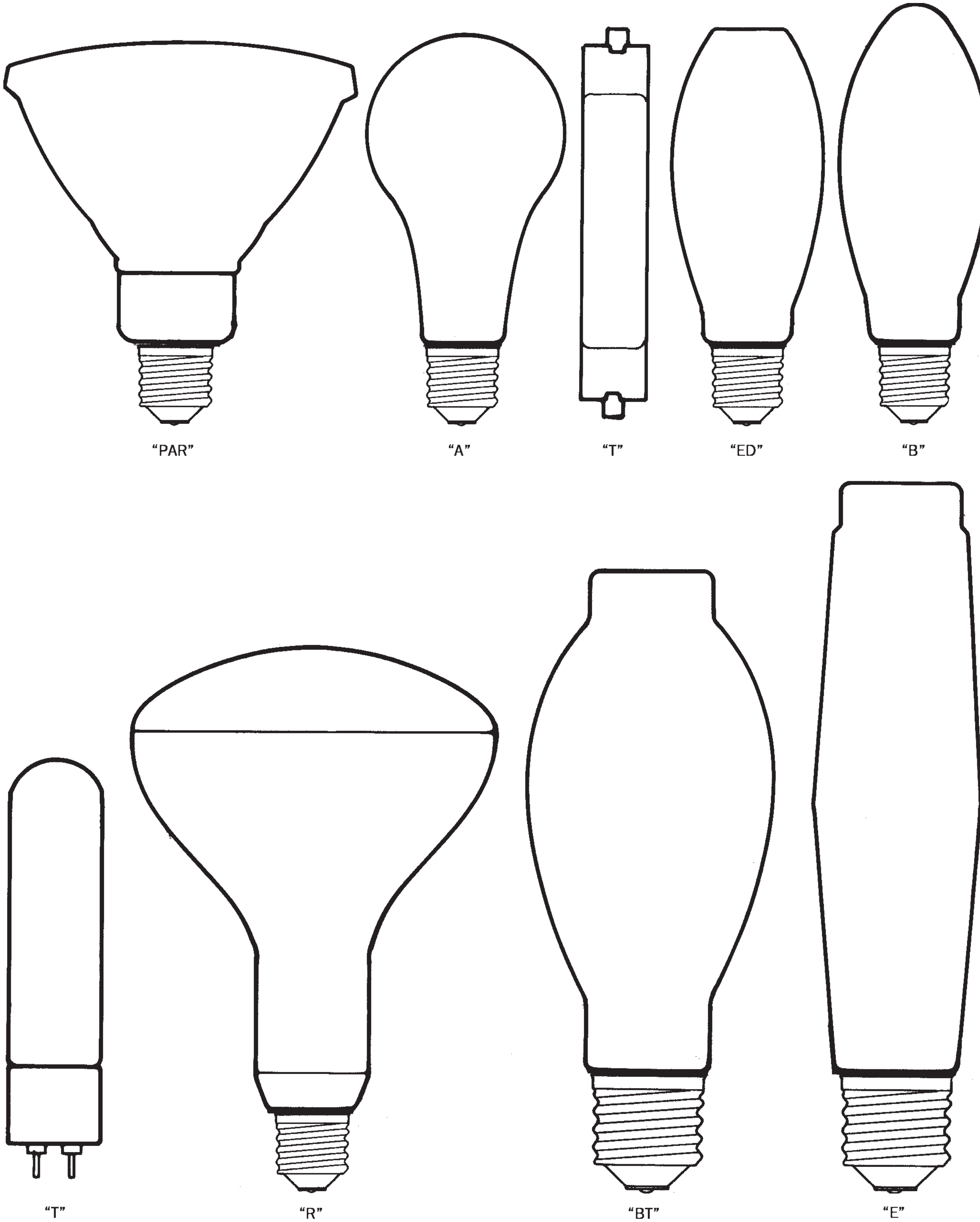


Figure 7.14 HID lamp shapes at one-half actual size.

H	mercury vapor lamp (*H* stands for for *hydrargyrum*, the Greek word for mercury and the source of its chemical symbol Hg)
M	*m*etal halide lamp
S or LU	high-pressure *s*odium lamp (*LU* is short for the trademarked name of several manufacturers' HPS lamps)
SB	*s*elf-*b*allasted mercury lamp (for incandescent retrofit)
T	self-ex*t*inguishing mercury or metal halide lamps (these stop operating if the outer bulb is broken to protect people from exposure to excessive UV radiation; the designation is omitted with non-self-extinguishing lamps.[1]
39	with mercury lamps, two-digit numbers denote electrical properties and kind of ballast required; lamps with the same numbers are electrically interchangeable (double numbers such as 43/44 indicate that the lamp will operate from more than one ballast).
100	with metal halide and HPS lamps, the number specifying nominal lamp wattage.
/C	phosphor-*c*oated (metal halide)
/D	*d*iffuse-coated (HPS)
/U	manufacturer-designated symbols appear after the next slant line; these commonly identify color or burning position (e.g., U = *u*niversal burning position).
/BD	*b*ase *d*own to horizontal ± 15°
/BU	*b*ase *u*p to horizontal ± 15°
/DX	*d*eluxe white phosphor
/HOR	base *hor*izontal ± 15°
/MED	*med*ium screw base
/T	*t*ubular bulb
/U	*u*niversal burning position

[1]Mercury and metal halide lamps will cause serious skin burn and eye inflammation from shortwave ultraviolet radiation after only a few minutes when the outer envelope of the lamp is broken or punctured if adequate shielding is not used.

For optical control, clear lamps offer a relatively small "point source" of 2⅛ in to 9½ in in length. The phosphor-coated lamps enlarge the optical size of the source to the outer bulb wall; although the phosphor coating enhances the lamps' color-rendering abilities, the increased optical size dictates the use of large reflectors for useful optical control.

Lamp Operation

As with fluorescent lamps, HID lamps require ballasts to regulate the arc current flow and to deliver the proper voltage to strike the arc. Electronic ballasts are more efficient and provide more precise control of the arc tube voltage over the lamp's life, resulting in more consistent color and longer life.

Extinction of a lamp occurs in one of three ways: (1) a power interruption of more than half a cycle, (2) a severe voltage dip of more than a few cycles, or (3) insufficient voltage maintained from the ballast.

Before the lamp will relight, it must cool sufficiently to reduce the vapor pressure to a point where the arc will restrike. The time required to cool depends partly on a luminaire's ability to dissipate heat. Typically in a luminaire, mercury vapor lamps will relight in three to ten minutes. Metal halide lamps require ten to twenty minutes to restrike; pulse-start metal halide lamps relight in four to eight minutes. High-pressure sodium lamps usually restrike in approximately one minute. "Instant-strike" HPS lamps have a second arc tube that produces light instantly after a momentary power interruption.

Light Output

Depreciation in light output during life occurs mainly because of the escape of electron-emissive material and tungsten from the cathodes to the walls of the arc tube. This depends in part on the frequency of starting; therefore, long burning cycles increase lamp life and lumen maintenance. Other factors affecting lumen maintenance are operating current and the current wave form produced by the ballast design.

The light output of metal halide lamps declines more rapidly than either mercury vapor or HPS lamps. With ceramic metal halide lamps, lumen maintenance is improved approximately 30 percent. Frequent starting is most harmful to metal halide, less harmful to HPS, and least harmful to mercury vapor lamps.

Lamp Life

Lamp life varies considerably depending on the kind of HID lamp and its burning orientation. The rated average life of HID lamps is the point at which approximately 50 percent of the lamps in a large group have burned out and 50 percent remain burning. Published lamp-life ratings are based on ten hours per start.

The normal mode of failure of a mercury vapor lamp is its inability to light. Almost all mercury vapor lamps have rated average lives of 24,000+ hrs (the plus sign indicates that in 50 percent of such lamps "burnout" occurs in excess of 24,000 hrs). It is wise to relamp before reaching the point of failure, however, because the lamps continue to operate long after they are a useful light source.

Metal halide lamps have rated average lives of 7,500 to 20,000 hrs, depending on lamp wattage. Lives of metal halide lamps are shorter than those of other HID lamps because of inferior lumen maintenance and the presence of iodides in the arc tubes. The normal mode of failure is the inability to light because of an increased starting voltage requirement. Metal halide lamps are particularly sensitive to frequency of starting. As with all lamps, over-wattage operation also shortens life.

Almost all HPS lamps have rated average lives of 24,000 hrs. Normal end of life occurs when the lamp begins to cycle on and off, the result of lamp voltage having increased to the point where the ballast voltage is insufficient to keep the lamp lighted. Over-wattage operation causes voltage to rise faster; slight under-wattage does not affect lamp life.

As with fluorescent lamps, the initial lumen rating for HID lamps is measured after the first one hundred hours of operation. This "seasoning" is necessary because the lamps depreciate rapidly during these first hundred hours, when cleanup of impurities takes place.

Dimming

It is possible to dim some HID lamps using special ballasts, but operating HID lamps at less than full output will produce color shifts and reduced lamp efficacy. As wattage decreases, the color-rendering properties of metal halide lamps approach the color of mercury vapor; HPS lamps approach the yellow-amber color of low-pressure sodium. mercury vapor lamps will retain their already inferior color properties reasonably well, but lumen maintenance and length of life are reduced.

LOW-PRESSURE SODIUM (LPS) LAMPS

Low-pressure sodium (LPS) lamps, although technically not high-intensity discharge sources, are used in limited applications. They have high efficacies—up to 200 lumens per watt—but their extremely narrow spectral range makes these lamps unsuitable for use in interiors (color plate 26).

The lamp, consisting of two tubes, one inside the other, has a mixture of neon and argon gas, plus sodium metal in the inner tube and an evacuated outer bulb. Initially, the arc discharge is through the neon and argon gas and, as the sodium metal heats up and vaporizes, the yellow-amber color of sodium is produced (figure 7.15).

The light produced by the LPS arc, consisting only of radiation in the yellow region of the visible spectrum, is monochromatic. No mercury is present in the discharge; UV radiation emission is not a concern if the outer bulb breaks. The LPS lamps require specific ballasts; no retrofit lamps exist.

In contrast to HID sources, LPS systems maintain constant lumen output over life and light output is unaffected by changes in ambient temperature. Normal end of life occurs when the lamp fails to start or warm up to full light output.

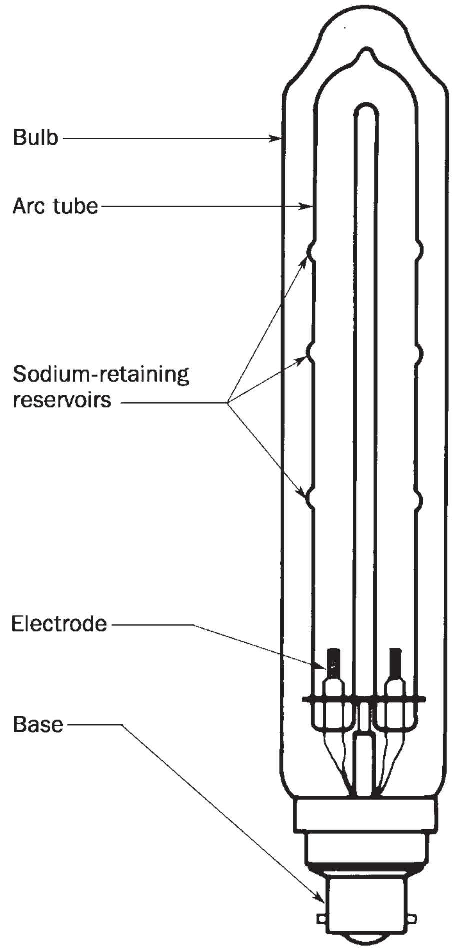


Figure 7.15 Low-pressure sodium lamp construction.

8 Auxiliary Equipment

All discharge sources and low-voltage incandescent sources require the use of auxiliary equipment to supply the correct current or voltage or both to the source.

Auxiliary equipment falls into two categories: transformers and ballasts. This auxiliary equipment consumes a small amount of electrical power, adding to the total amount of wattage used by the lighting system.

TRANSFORMERS

Low-voltage light sources require the use of a *transformer* to step down the standard building service of 120 V to 12 V. The nominal 120 V building service can vary between 115 V and 125 V; some low-voltage light sources operate at 6 V or 24 V. Transformers are placed either within (*integral* to) the luminaire or in a *remote* location.

The smaller size of many low-voltage light sources allows for the design of smaller luminaires. With recessed luminaires the transformer is hidden above the ceiling and out of view. With surface- or pendant-mounted luminaires that have their transformers enclosed within the housing, however, the bulk of the luminaire is increased. Where ceiling conditions permit, surface- and pendant-mounted luminaires can be designed with the transformer recessed in the ceiling and out of view.

Track-mounted luminaires usually contain their transformers. It is also possible to provide low-voltage service to a length of track, locating the transformer in the ceiling or in an ancillary space. The high amperage of low-voltage lamps strictly limits the number of track luminaires per transformer (W ÷ V = A): a 50 W, 12 V lamp draws the same amperage as a 500 W, 120 V lamp; therefore, a 20-ampere-rated track can service only four 50 W lamps (50 W × 4 ÷ 12 V = 16.7 A). This problem is reduced by the use of 50-amp track, which permits ten 50 W, 12 V lamps to be installed on a single track circuit (50 W × 10 ÷ 12 V = 41.7 A).

If remote transformers are used to maintain the compactness of the lighting element, the increased distance between the source and its transformer requires larger wire sizes to prevent a *voltage drop* from occurring over the longer wiring run. See table 9 in the Appendix.

Two kinds of transformers are manufactured for low-voltage lighting: magnetic (core-and-coil) and electronic (solid-state).

Magnetic transformers use copper wound around a steel core, which is *induc-*

tive by nature. Magnetic transformers are relatively large and heavy. Properly sized for the lamp load, they have a long life expectancy. They sometimes cause a noise problem by producing an audible 60-cycle "hum." *Toroidal* (doughnut-shaped) magnetic transformers are quieter, but they also hum when controlled by some kinds of electronic dimmers. The hum grows with the number of luminaires in a room, and the luminaires, if improperly designed, will resonate with their transformers.

Electronic transformers use electronic circuitry, which is *capacitive* by nature. Electronic transformers are compact, lightweight, and quiet. But their life is shorter than magnetic units, premature failures are common, and they are incompatible with some dimmers. The small dimensions of electronic transformers outweigh many of these flaws, however. The designer must consult the dimmer manufacturer to ensure the compatibility of transformers and dimmers.

BALLASTS

All lamps, except incandescent ones, require a *ballast*. Every discharge source has negative resistance characteristics. If the arc discharge is placed directly across a non-regulated voltage supply, it will draw an unlimited amount of current almost instantly and will be quickly destroyed. Therefore, a current-limiting device called a ballast is inserted between the discharge lamp and the power supply to limit the electric current flow through the arc discharge (figure 8.1).

Besides limiting the current flow, the ballast also provides the correct voltage to start the arc discharge. It transforms the available line voltage to that required by the lamp.

Traditionally, ballasts have not been interchangeable. Most ballasts are designed to provide the proper operating characteristics for only one kind of lamp. For example, 175 W M57 metal halide lamps are inoperable on ballasts intended for 175 W H39 mercury vapor lamps, and vice versa.

Newer electronic ballasts are designed to operate more than one connected load. For example, several manufacturers offer ballasts that can operate either one, two, or three fluorescent lamps.

Lamp wattage is controlled by the ballast, not by the lamp. If a 100 W HPS lamp is operated on a 400 W ballast, it will operate at 400 W, to the detriment of the lamp's performance. This may also lead to premature ballast failure.

Unlike incandescent lamps, the rated wattage of a discharge lamp is the wattage

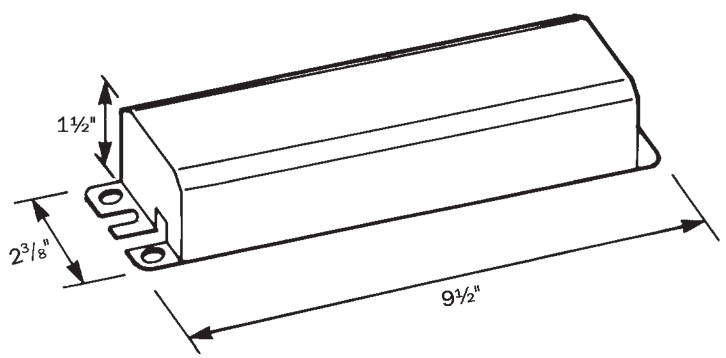


Figure 8.1 Typical F32T8 120 V ballast.

at which it is designed to operate, not the wattage at which it will operate. Therefore, it is impossible to reduce the wattage of a discharge system simply by changing the wattage of the lamps. The ballasts must also be changed.

Two-lamp fluorescent ballasts are used frequently to reduce ballast cost and installation cost per unit of light. They are available for two-lamp series operation or two-lamp parallel operation.

Two-lamp *series* designs are more common because they offer the lowest cost and the minimum size and weight. Only two lamp leads are supplied from the ballast. Both lamps go out when one lamp fails; the good lamp remains undamaged.

Two-lamp *parallel* designs have two independent ballast circuits and therefore are more expensive than two-lamp series designs. Three or six lamp leads are supplied from the ballast. Failure of one lamp leaves performance of the second lamp unaffected.

Electromagnetic Ballasts

Until the 1980s, all discharge ballasts were of the *electromagnetic* kind. The electromagnetic ballast consists of two copper or aluminum wire coils around a common core of steel laminations. This assembly converts electrical power into a form appropriate to start and regulate the lamp.

The ballast usually consists of a transformer, inductance coils, and a capacitor. The transformer converts the service voltage of the lighting circuit to the starting voltage required for the lamp. The *inductance coil* limits the current that can be drawn by the lamp, but in so doing introduces *inductive reactance* into the circuit. The *capacitor* realigns the phase relationship between voltage and current; it is a controlling device that consumes no electrical power.

The capacitor improves the ballast's *power factor* so that it uses energy more efficiently. An electromagnetic ballast that is equipped with a capacitor is called a *high-power-factor* ballast.

Power Factor

The *power factor* of a ballast is the measurement of how effectively the ballast converts the voltage and current supplied by the electrical distribution system to the power delivered by the ballast to the lamp. Perfect phase relationship would result in a power factor of 100 percent.

$$\text{Power factor} = \frac{\text{Input watts (W)}}{\text{Line volts (V)} \times \text{Line amps (A)}}$$

The power factor of an inductive circuit is lagging (figure 8.2) and that of a capacitive circuit is leading. When discharge lamps are operated in conjunction with simple

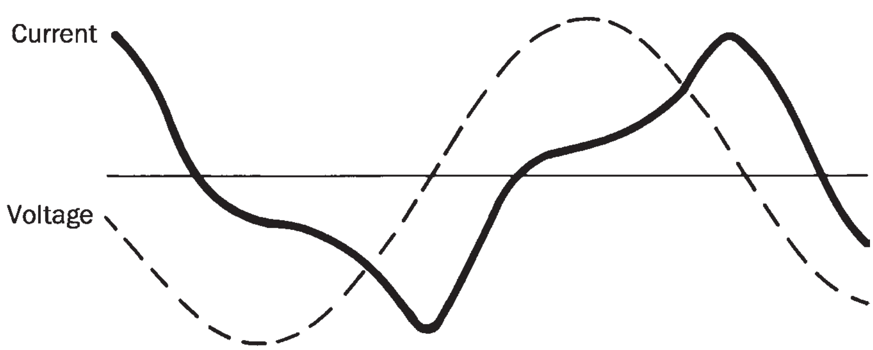


Figure 8.2 Power factor.

inductive ballasts, the overall power factor is 50 to 60 percent. With a capacitor, the leading current drawn by the capacitor compensates for the lagging current in the remainder of the circuit, improving the power factor.

Ballasts are classified according to one of the following three categories:

High power factor: 90% or greater

Power factor corrected: 80 to 89%

Low (normal) power factor: 79% or less

High-power-factor ballasts use the lowest level of current for the specific amount of power needed; this reduces wiring costs by permitting more luminaires on branch circuits. Low-power-factor ballasts use higher levels of current—approximately twice the line current needed by high-power-factor ballasts—allowing fewer luminaires per branch circuit and increasing wiring costs.

Power factor is not an indication of the lamp-ballast system's ability to produce light; power factor measurements pertain only to the ballast's ability to use the power that is supplied. Thus, power factors are invalid as a multiplier in determining light output values.

Lamp-Ballast System Efficacy

The initial lumen and mean-lumen ratings published by lamp manufacturers are based on the operation of the rated lamps by a *reference ballast*. This is a laboratory instrument that is used to establish a baseline, or reference conditions, so that commercially available ballasts can be compared against the same reference. Some commercially available ballasts operate lamps more efficiently than the reference; others operate lamps less efficiently.

In practice, when a lamp is operated by a commercially available ballast, it usually provides fewer lumens than the rated amount. Because of the electrical resistance created by the passage of a current through the core-and-coil of an electromagnetic ballast, some power is converted to heat. This lost power, called *ballast loss*, is unusable for producing light from the lamp.

The disparity between light provided by the reference ballast and the commercially available ballast is called the *ballast factor*. The ballast factor is the ratio of light output produced by lamps operated by a commercially available ballast to that which is theoretically supplied by lamps powered by a laboratory-reference ballast.

$$\text{Ballast factor} = \frac{\text{Lamp lumen output when operated with commercial ballast}}{\text{Lamp lumen output when operated with laboratory-reference ballast}}$$

The term "ballast factor" implies that this is a property of the ballast; it is actually a property of the lamp-ballast system. Some ballasts have different factors for different lamps. That is, they have one ballast factor for operating standard lamps and another for operating energy-saving lamps.

Ballast factors can be greater than 1.0. A commercial ballast can operate a lamp in a way that produces more lumens than when the lamp is operated under reference conditions.

The *ballast efficacy factor* is a ratio of the ballast factor to the input watts of the ballast. This measurement is used to compare the efficiency of various lamp-ballast systems. Ballast efficacy factors are meaningful only for comparing different ballasts when operating the same quantity and kind of lamp.

$$\text{Ballast efficacy factor} = \frac{\text{Ballast factor}}{\text{Ballast input watts}}$$

For a given lighting system, the ballast factor is an indication of the amount of light produced by the lamp-ballast combination; the input watts are an indication of the power consumed.

For example, a ballast with a ballast factor of 0.88 using 60 W of input power has a ballast efficacy factor of 1.47 ($0.88 \times 100 \div 60 = 1.47$). Another ballast using the same input power with a ballast factor of 0.82 has a ballast efficacy of 1.37 ($0.82 \times 100 \div 60 = 1.37$). The first ballast therefore offers greater efficacy because it has a higher ballast efficacy factor (1.47 versus 1.37).

An electromagnetic ballast operating from an alternating current source produces a sound called "hum." The degree of hum varies depending on the kind of ballast. To aid in the selection of ballasts, manufacturers give their ballasts a sound rating that ranges from *A* (the quietest, at 20 to 24 decibels) to *F* (the loudest, at 49 decibels and above).

Electronic Ballasts

The *electronic* ballast, based on an entirely different technology from the electromagnetic ballast, starts and regulates lamps with electronic components rather than the traditional core-and-coil assembly. The lighting systems they operate convert power to light more efficiently than systems run by electromagnetic ballasts.

Rather than produce more light output, electronic ballasts are usually designed to produce the same quantity of light as electromagnetic ballasts, but they use less power and thereby reduce energy costs.

HID electronic ballasts provide better output regulation (current and power), independent of input voltage variations or lamp wattage variations. This keeps color output (CCT and CRI) consistent and lumen output more uniform. Compared to electromagnetic systems, HID electronic ballasts provide improved performance in starting, normal, and restrike operations.

The humming sound associated with electromagnetic ballasts results from the vibration of the steel laminations in the core and coil. Because electronic ballasts do not have the laminated core and coil, they are 75 percent quieter than comparable A-rated electromagnetic ballasts.

Electronic ballasts operate fluorescent lamps at higher frequencies than electromagnetic ones, with the advantages that flicker is eliminated and lamp efficacy is increased. Both of these advantages occur because the lamp phosphors are under more constant excitation with high-frequency operation.

Electronic ballasts are also smaller and lighter in weight than electromagnetic ones, typically weighing less than half as much because the electronic components are lighter than the metal components of the core-and-coil assembly. Because electronic ballasts consume fewer watts than electromagnetic ballasts, they also produce less heat. This cooler operation yields significant savings in air-conditioning costs.

Air-Conditioning

The air-conditioning load caused by electric lighting derives from the total lighting system, including lamps and ballasts. Each *kilowatt* (kW) of electric power used by the lighting system adds 3,412 British thermal units (BTUs) to the air-conditioning load.

One ton of air-conditioning = 12,000 BTU. Therefore, every 3.5 kW of lighting requires one-ton of air conditioning.

$$\frac{12{,}000}{3{,}452} = 3.5 \text{ kW}$$

Fluorescent Dimming Ballasts

Electronic fluorescent *dimming* ballasts will dim T5, T5 high-output, T8, and T12 fluorescent lamps to 1 percent of measured light output (10 percent of perceived light). (Light output as it is measured is different from light perceived by the eye. See page 143.) For four-pin compact fluorescent lamps (T4 quad-tube, T4 triple-tube, and T5 long twin-tube), electronic dimming ballasts will dim to 5 percent of measured light output (22 percent of perceived light). New lamps must first be operated ("seasoned") for one hundred hours at full power prior to dimming to achieve proper dimming performance and ensure average rated lamp life.

Fluorescent Heater-Cutout Ballasts

Heater-cutout electromagnetic ballasts have an electric circuit that removes the voltage supplied to the electrode heaters in rapid-start fluorescent lamps after the lamps are ignited and operating. Heater-cutout ballasts consume approximately 20 percent less input power than do standard electromagnetic energy-efficient ballasts; lumen output is reduced by approximately 12 percent.

Other Ballasts

In addition to standard ballasts, several kinds of *energy-saving* ballasts are made. These fall into two categories: (1) ballasts that save energy by reducing wattage consumed as well as reducing light output, and (2) ballasts that, because of refinements in design, save energy chiefly by reducing wattage loss in the ballasts themselves.

Class P ballasts are equipped with automatically resetting thermal protectors. These turn off the power when the operating temperature exceeds the limits specified by Underwriters Laboratories (UL) to prevent overheating. When the ballast cools, the protector resets, restoring operating power to the ballast.

The UL symbol applied to luminaires indicates that Underwriters Laboratories has examined a sample unit and determined that it complies with appropriate safety standards. It indicates that when properly installed, such a luminaire will operate safely. The UL label is also applied to components, such as transformers and ballasts, to signify that the components meet safety requirements. (The UL label indicates overall luminaire safety when applied to the luminaire and component safety when applied to the components. Different labels and markings are used for various applications, but all make use of the trademark UL circle.)

COMPARATIVE FLUORESCENT LAMP-BALLAST SYSTEMS

Ballast kind	Typical input power (W)	Typical ballast factor	System efficiency (Lumens/W)
Two F32T8/RS lamps, 32 W each			
electromagnetic energy-efficient	70	0.94	78
electromagnetic heater-cutout	61	0.86	82
electronic ballast rapid-start	62	0.88	82
electronic ballast instant-start	63	0.95	87
Two F40T12/RS/ES lamps, 34 W each			
electromagnetic energy-efficient	72	0.87	68
electromagnetic heater-cutout	58	0.81	78
electronic ballast rapid-start	60	0.85	79

Light Control 9

Directional sources, commonly called reflector lamps, such as AR, MR, PAR, and R lamps, have built-in optical systems. All other electric light sources require external devices to modify their distributions in order to be useful in architectural applications.

These modifications have two purposes: (1) to direct light to where it is wanted and (2) to block light from where it is unwanted—to shield the lamp from viewing angles that would otherwise cause glare. The control of light direction is accomplished by three methods: reflection, transmission, and refraction.

REFLECTION

Reflection is the return of light from a surface; it occurs when a portion of the light falling on the surface is thrown back by that surface just as a ball bounces back from the floor. Three kinds of reflection are involved in the control of light: specular, semi-specular, and diffuse.

Specular reflection

A smooth, highly polished surface, such as a mirror, alters the direction of a beam of light without changing its form. The angle of reflection is equal to the angle of incidence—a property that makes specular materials ideal where precise beam control is desired (figure 9.1).

Because *specular* surfaces are virtually mirrors, their own surfaces are almost invisible; they may appear dark or bright, depending on the observer's position and on the luminance of the reflected image.

Semi-specular (spread) reflection

Irregular surfaces, such as those that are corrugated, hammered, brushed, sandblasted, or etched, partially disperse or "spread" the reflected beam. The greatest intensity, however, is still reflected at an angle near the angle of incidence (figure 9.2).

Semi-specular materials appear with highlights or streaks of higher brightness on a background of lower brightness. In interiors, they are often used as elements of sparkle. In luminaires, semi-specular materials produce a moderately controlled beam that is smooth and free from striations.

Diffuse reflection

Rough or matte surfaces neutralize the directional nature of the incident beam.

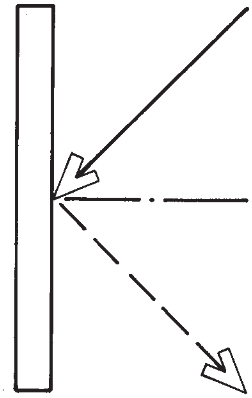


Figure 9.1 Specular reflection.

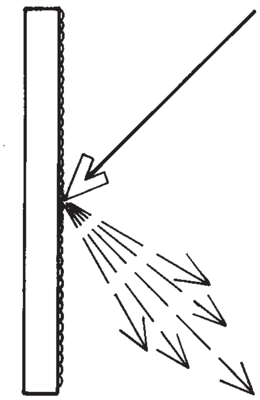


Figure 9.2 Semi-specular (spread) reflection.

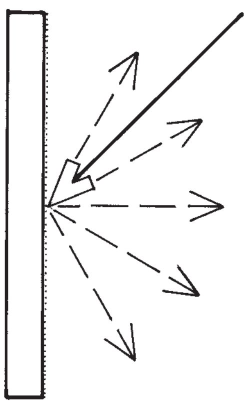


Figure 9.3 Diffuse reflection.

Light is reflected from each point in all directions, with maximum intensity perpendicular to the surface (figure 9.3).

Sand on the beach is an example of a *diffuse* reflecting surface. There are no bright spots; the surface appears the same from all angles of view. In interiors, this quality is often desirable for walls, ceilings, and work surfaces. In luminaires, diffusely reflecting materials are used to produce wide distributions of light.

Reflector Contours

Specular and semi-specular surfaces formed into geometric contours use the *law of reflection* for beam control: the angle of incidence equals the angle of reflection. This is the same law that governs the rebound of a billiard ball off a cushion.

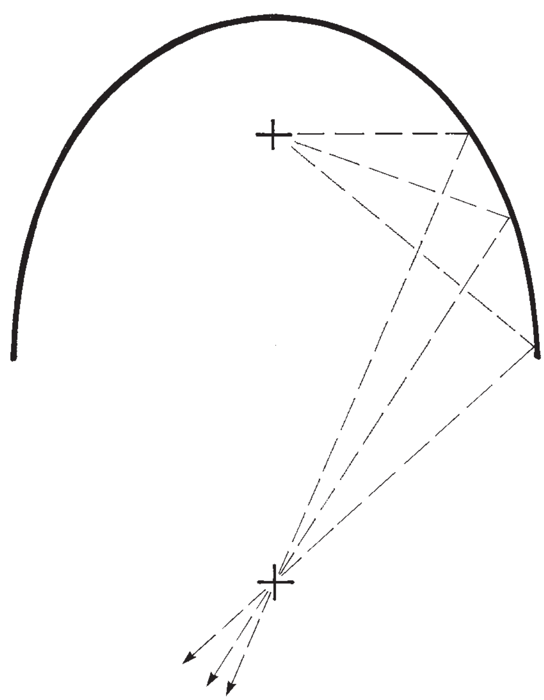


Figure 9.4 Elliptical contour.

Specular reflection is a primary technique for modifying and controlling the direction and distribution emitted by a light source. Specular reflection takes light that would otherwise be lost or wasted within a luminaire or emitted at glaring angles and conserves it by redirecting the light into a room or onto a surface at useful angles.

In addition to this more efficient use of light, the application of properly contoured reflectors produces predictable luminaire distributions and controlled room brightness patterns. Specular reflector contours commonly used in luminaires include actual or modified ellipses, parabolas, and circles.

Elliptical contour

Ellipses have two focal points; a ray of light originating at one focal point is reflected through the second focus. This produces a divergent beam; its spread depends on the distance between the two foci (figure 9.4). Most downlights use reflectors with exact or modified elliptical shapes. A special use of this contour produces a beam that passes through a small, inconspicuous opening flush with the ceiling plane.

Parabolic contour

The parabola is a special form of the ellipse, in which the two foci are far apart. A ray of light originating at the exact focal point of a perfectly shaped parabolic contour is redirected in a direction parallel to the axis of the reflector, producing a beam of parallel rays (figure 9.5). The filament or source is never an actual point; this results in a degree of beam-spread that depends on the size of the source and the diameter of the reflector.

In its pure form, the parabolic contour is used for searchlights, spotlights, and directional equipment where a concentrated beam and a limited spread of light are desired. The beam is often given additional spread by passing it through a diffusing or refracting lens, as is done with many reflector lamps.

Circular contour

The circle is also a special form of the ellipse, one where both foci are coincident; it is the opposite of the parabola. A ray of light originating at the focal point of a circular contour is reflected back through the same point (figure 9.6). It is used separately or in combination reflectors called *compound*

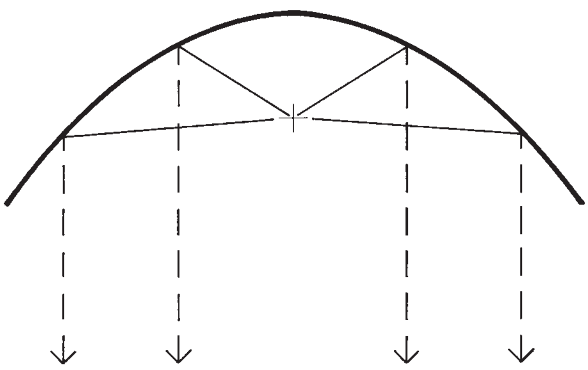


Figure 9.5 Parabolic contour.

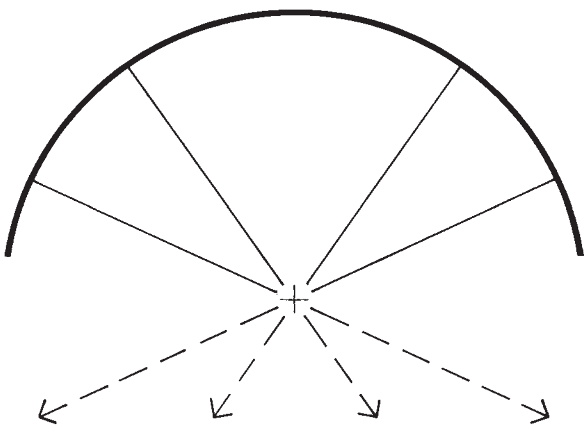


Figure 9.6 Circular contour.

contours to redistribute light that would be otherwise misdirected or trapped.

Other reflector contours

Compound contours, which provide asymmetric distribution or maximum beam-spread with a shape of minimum dimension, are useful for producing uniformity of luminance from a position close to the surface being lighted; for example, to light the ceiling in a low-height room (figure 9.7).

Innumerable other possible reflector contours can be mathematically defined and tailored for a particular function. These reflectors do not have a specific focal point.

Reflectors

Specular reflectors

Almost all reflector design presumes a compact "point" source of light or a linear source of light at the focus or other precise location. The most compact source is an incandescent filament in a clear bulb.

Large variations in beam control occur, however, with the use of lamps that emit light from a larger area, such as an arc tube or a phosphor-coated bulb or tube. In these cases the bulb or tube, rather than the filament, is the actual light source. This kind of lamp is both a large source displaced from the focus and a diffuse emitter. The result is a diffuse or less precisely defined beam and a reduced projection distance.

The first reflectors for electric luminaires were designed by trial and error or by "longhand" mathematics (figure 9.8). Today, computer-aided reflector design accounts for all of the characteristics of a light source and optimizes a reflector contour.

Semi-specular reflectors

Although clear incandescent lamps in specular reflectors produce efficient beam control, there is often a need to smooth out irregularities in the beam. These striations are reflected images of the filament coil. They are eliminated by a slight diffusion of the beam, accomplished by using (1) an inside-frosted lamp, (2) a lightly etched, faceted, or hammered reflector surface, or (3) a moderately diffusing lens in the beam path.

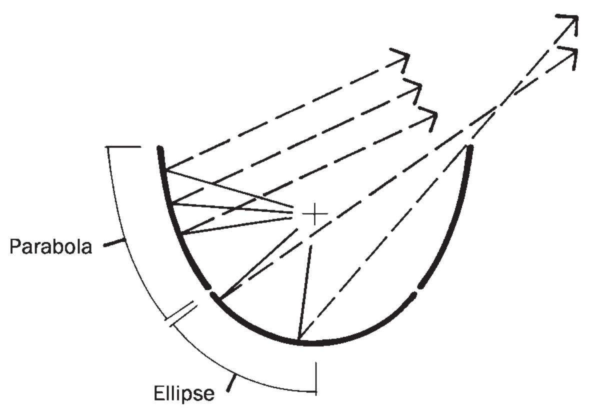


Figure 9.7 Compound contour for maximum beam-spread (often used to produce asymmetric distribution).

Diffuse reflectors

The reflection of light from a perfectly diffuse, flat surface is multidirectional, giving a circular distribution curve; the angle of reflection is independent of the angle of incidence. With incident light dispersed in all directions, the beam is wide (figure 9.9); because of this lack of directional control, long projection distances are impractical.

The shape of a diffuse reflector has little influence on the resulting direction and distribution of light. Diffuse reflectors are often useful in luminaires that provide uniform, ambient brightness in a space, but they are unable to direct light toward a surface, such as the workplane.

Reflector materials

Aluminum is the material most frequently used for the fabrication of reflectors. It can be stamped, spun, hydroformed, or extruded into almost any desired shape or contour; it can be processed chemically and electrically to make it more specular; and it can be sandblasted or etched chemically to provide varying degrees of semi-specular reflection.

A hard, protective surface layer of high transparency produced by the anodizing process prevents scratching and abrasion of specular aluminum surfaces and makes cleaning practical.

TRANSMISSION

Transmission of light through a material is affected by two things: (1) the reflections at each surface of the material and (2) the absorption and redirection within the material (called refraction; see page 111). Just as a continuous degree of reflection exists from mirrored, fully specular surfaces to matte, fully diffusing ones, a similarly continuous degree of transmission exists from fully transparent, clear materials to fully diffusing, translucent ones.

Direct transmission

Transparent materials leave the light distribution unchanged (figure 9.10). They are used as protective covers for absorbing or reflecting infrared or ultraviolet radiation or where a change in the color of light is desired while maintaining the light distribution pro-

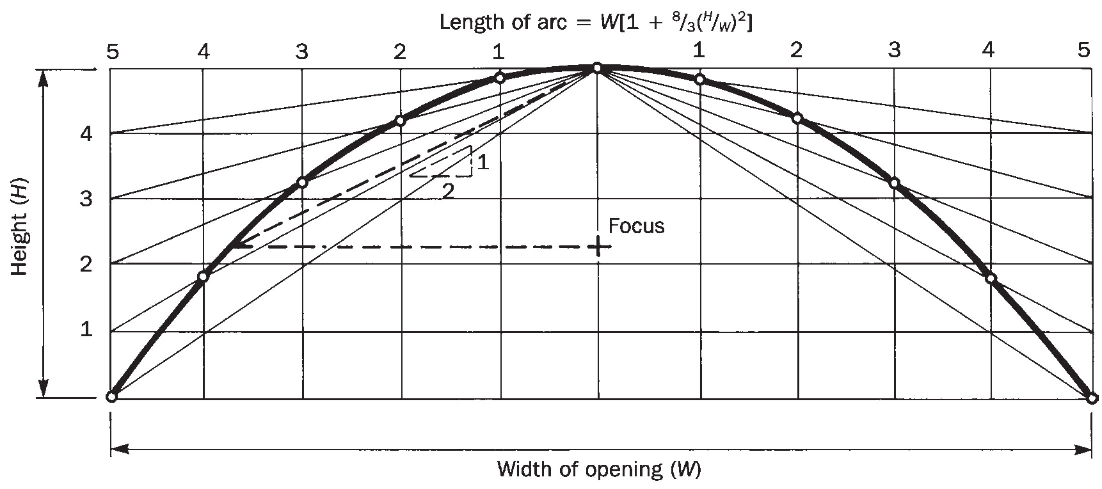
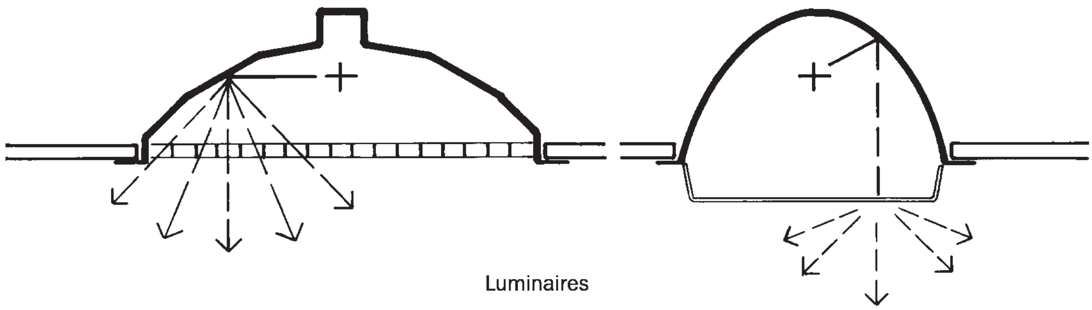
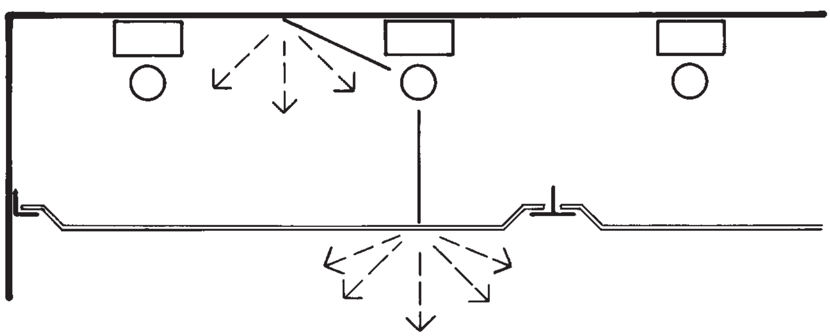


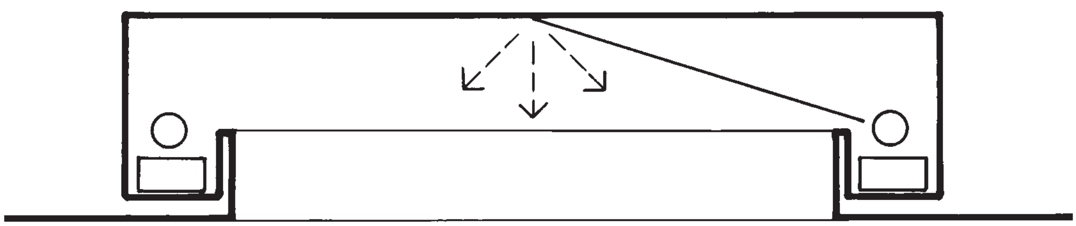
Figure 9.8 Parabolic reflector construction guide.



Luminaires



Self-luminous ceilings and walls



Coffers and coves

Figure 9.9 Diffuse reflector techniques.

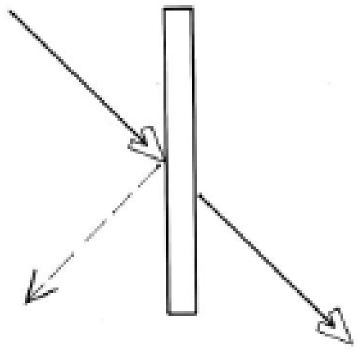


Figure 9.10 Direct transmission. Some first-surface reflection occurs with all forms of transmission.

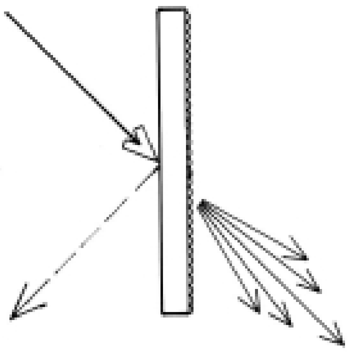


Figure 9.11 Semi-diffuse (spread) transmission.

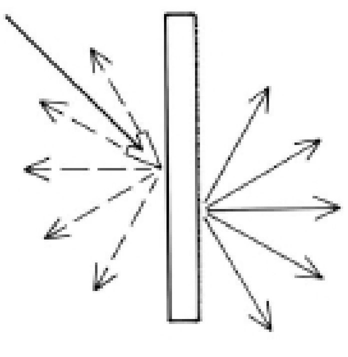


Figure 9.12 Diffuse transmission.

duced by reflecting contours. Because the light source remains visible, materials such as clear glass and plastic are ineffective for glare control.

Semi-diffuse (spread) transmission

Translucent materials emit light at wider angles because of configurations on at least one side of the material (figure 9.11). A slight redirection of the transmitted beam is achieved by minor surface irregularities, such as shallow facets or flutes, which smooth out imperfections and striations. A greater degree of diffusion is achieved by etching, sandblasting, hammering, and matte aerosol sprays applied to the outer surfaces; or the interior of the material is modified to achieve the diffusion. Semi-diffuse materials provide lamp concealment and glare control.

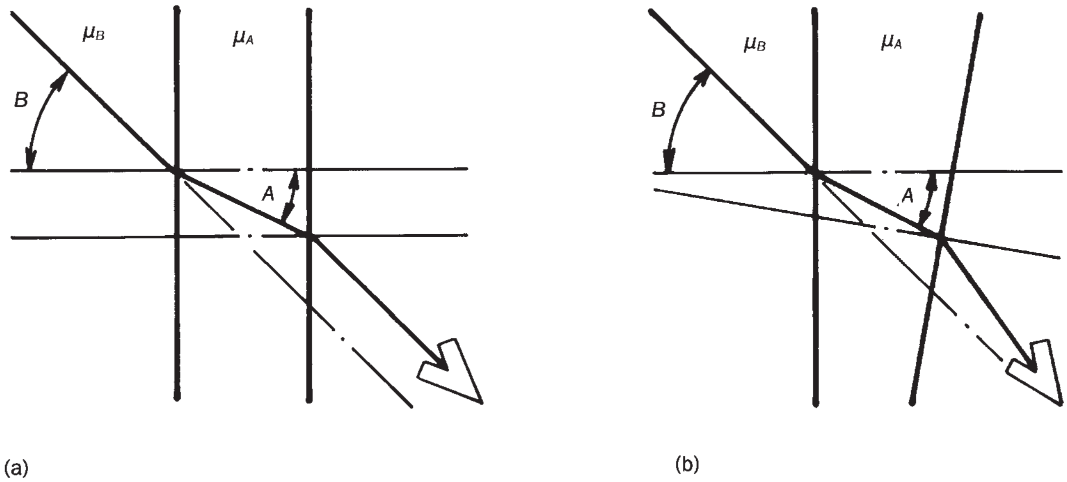
Diffuse transmission

Diffuse transmission disperses light in all directions and eliminates the directional quality of the beam (figure 9.12). Full diffusion is achieved by using opal glasses and plastics that incorporate microscopic particles and remove all directionality from the transmitted beam.

REFRACTION

When a straw is placed in a clear glass of water, it appears to bend at the point where it enters the water. This is because the speed of light changes when a light ray passes from air to water; the phenomenon is called *refraction*.

A similar result occurs when light passes from air to clear glass and plastics. When these transparent materials are formed into prisms or lenses, they become techniques for controlling the direction and, consequently, the distribution of light.



μ = *Index of refraction*

$$\sin B = \left(\frac{\mu_A}{\mu_B}\right)\sin A$$

Figure 9.13a and b The index of refraction is the ratio of the sines of the angles of incidence of a ray of light passing from one medium (usually air) into another medium (such as water, glass, or plastic).

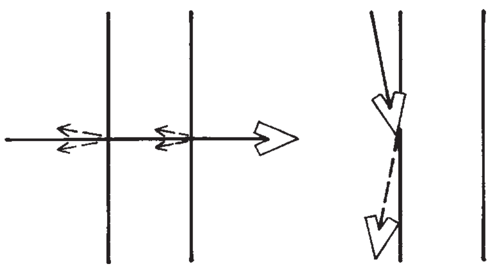


Figure 9.14 Deviation with index of refraction.

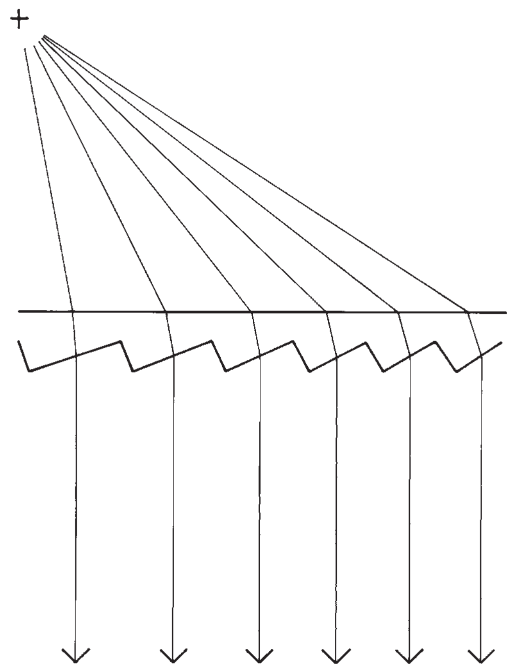


Figure 9.15 Prismatic action.

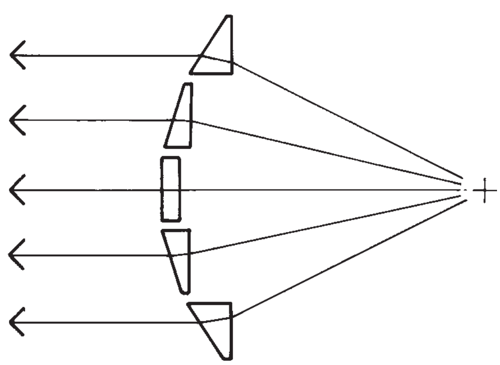


Figure 9.16 A lens is a system of prisms.

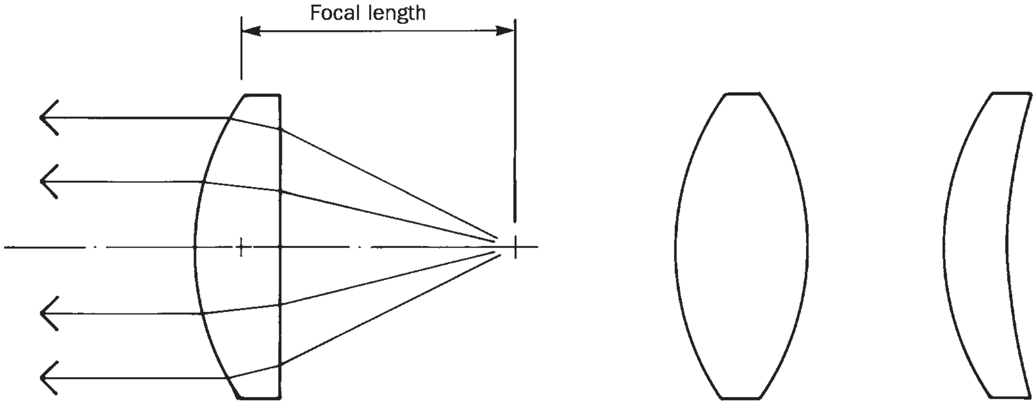


Figure 9.17 Convex lens.

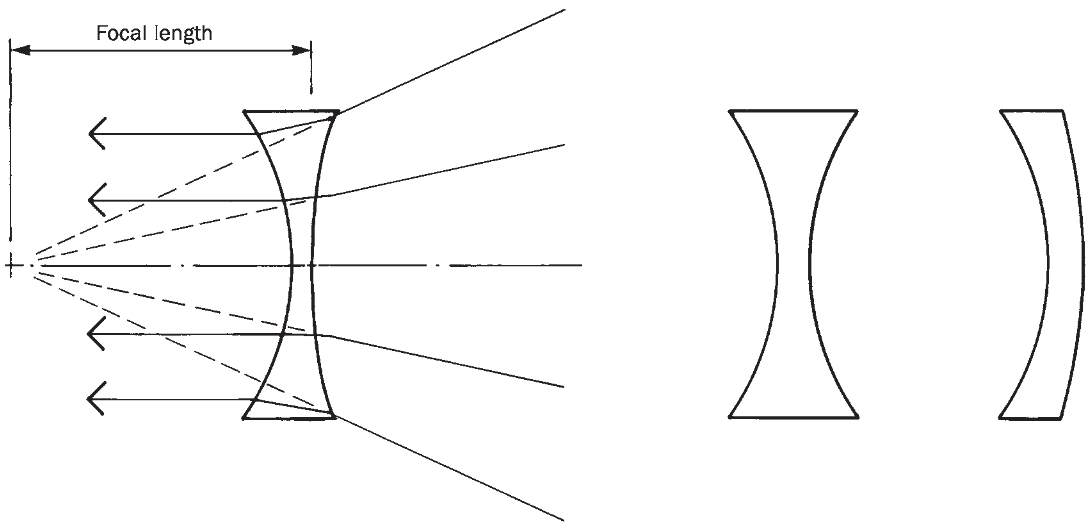


Figure 9.18 Concave lens.

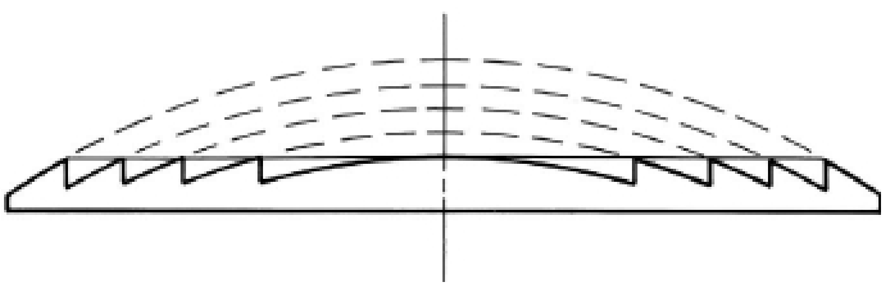


Figure 9.19 Fresnel lens.

Prisms

A beam of light is displaced at the surface of a transmitting material. If the material is formed with two parallel "faces," the displacements neutralize each other; no angular change in the direction of the beam occurs, only a slight displacement (figure 9.13a). If the opposite faces are not parallel, the unbalanced refraction permanently alters the direction of light (figure 9.13b).

Light rays deviate toward the perpendicular when entering a material with a higher index of refraction and deviate away from the perpendicular when entering material with a lower index (figure 9.14).

A *prism* is a transparent body bounded in part by two nonparallel faces. A beam of light projected through one face is emitted in a different direction through another. By providing the proper angle between prism faces, light is emitted in a desired direction (figure 9.15).

Lenses

A *lens* is formed by two opposite refracting surfaces, which have a common axis. It may be thought of as a multiple array of prisms with a continuously changing *included angle* to produce an organized distribution of light (figure 9.16). Two basic kinds of lens systems are used: convex and concave.

The *convex* (*positive* or *converging*) *lens* is thicker in the middle than it is at the edges. Its focal point lies on the axis, at the

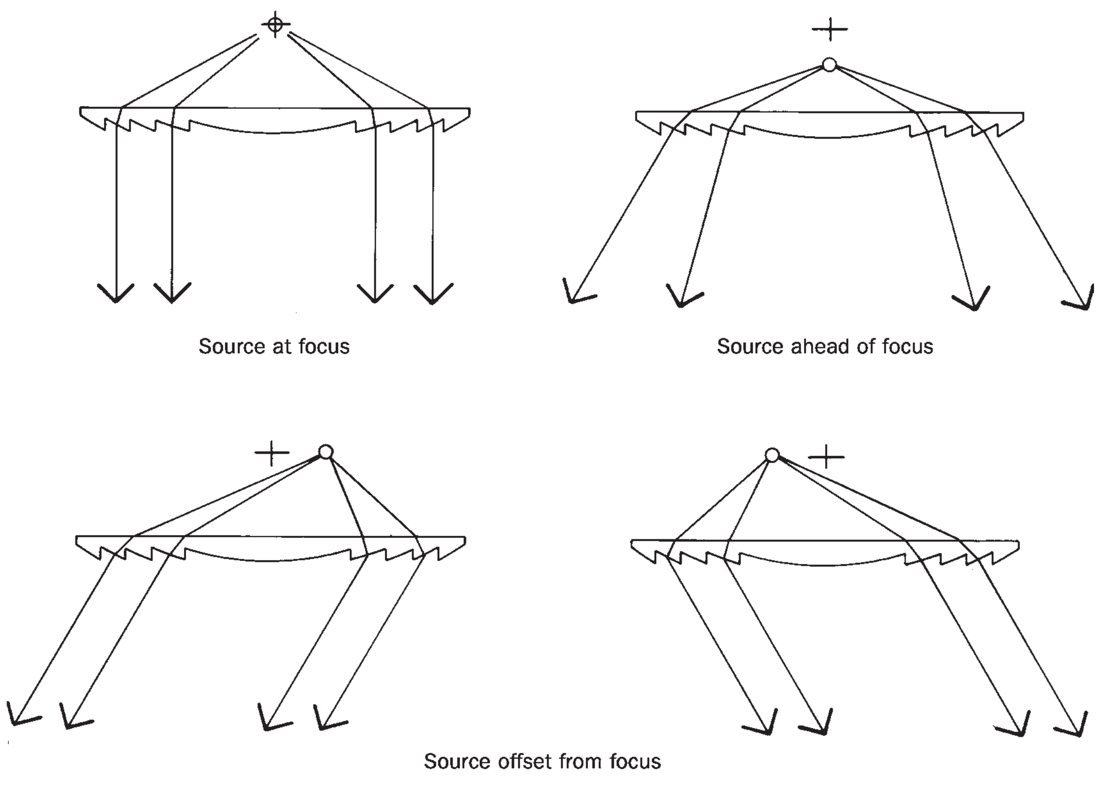


Figure 9.20 Distribution of light through a Fresnel lens.

point where the diverging rays from the source are refracted to produce a parallel beam of light (figure 9.17).

The *concave* (*negative* or *diverging*) *lens* is thinner in the middle than it is at the edges. This causes a parallel beam of light to diverge. The focus is called a virtual focal point; it is the artificial point at which the diverging rays would meet if they were traced backward as straight lines through the lens (figure 9.18).

Because refraction takes place at the surface of the material, with the direction of the ray unchanged between surfaces, part of this transmitting material can be removed without affecting the optical control. A convex lens with sections of the glass removed produces a lens that is thinner and lighter in weight.

The *Fresnel* lens, which is based on this principle, consists of a series of concentric lens sections regressed into a planar array (figure 9.19). It is named for the French physicist Augustin Jean Fresnel (1788–1827), who developed the lens for use in lighthouses. In luminaires, the Fresnel lens produces a concentrated beam of light while also reducing the brightness of the source, providing a degree of glare control.

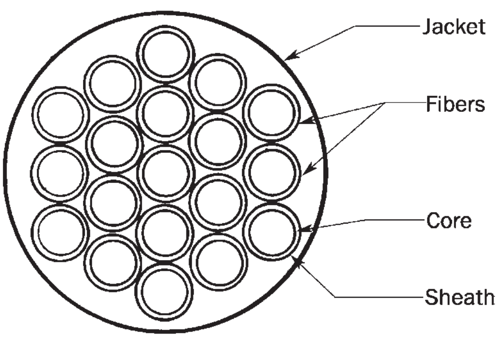


Figure 9.21 Enlarged section of optical fiber.

The Fresnel lens has a short focal length. A light source located at this focus produces a single, concentrated beam of light with parallel rays. When the light source is positioned at points other than the primary focus of the optical system, the lamp-refractor combination produces either a spread or asymmetric distribution (figure 9.20).

Glasses and plastics that incorporate a regular pattern of small prisms or other refractive elements are called *prismatic lenses*. They do not concentrate the distribution of light the way Fresnel lenses do; prismatic lenses spread the distribution of the source but also reduce its luminance, providing a degree of glare control.

Total Internal Reflection

Total internal reflection occurs when light passes into a transparent medium, such as glass or plastic, at an appropriate angle and travels inside the medium repeatedly reflecting from side to side. Edge lighting and light transmission through rods are examples of this phenomenon.

Fiber optics

With *fiber optics*, light entering one side of a glass or plastic fiber of optical quality is transmitted to the other end by the process of total internal reflection. Light rays that strike the core at the acceptance angle are reflected back and forth inside the core and travel to the other end of the fiber in a zigzag path of successive reflections.

In use, a single, large-diameter fiber is impractical because it lacks flexibility. To increase flexibility, a large number of small-diameter fibers are clustered together in a *bundle*. In order to prevent light leaking from one fiber to another, each is coated with a transparent sheath that has a lower *refractive index* than the fiber (figure 9.21). The sheathing process protects the surfaces of the fiber and allows the bundle to be embed-

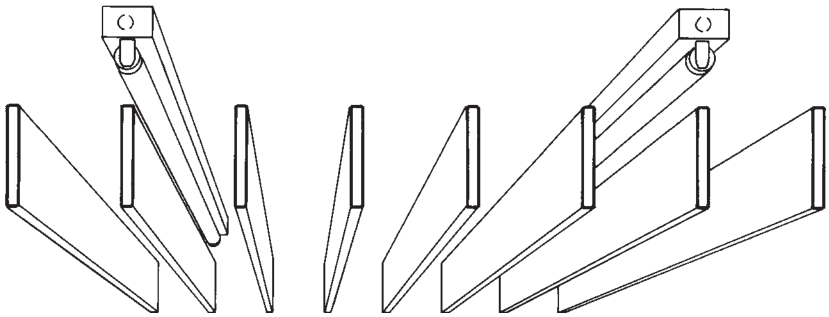


Figure 9.22 Baffles.

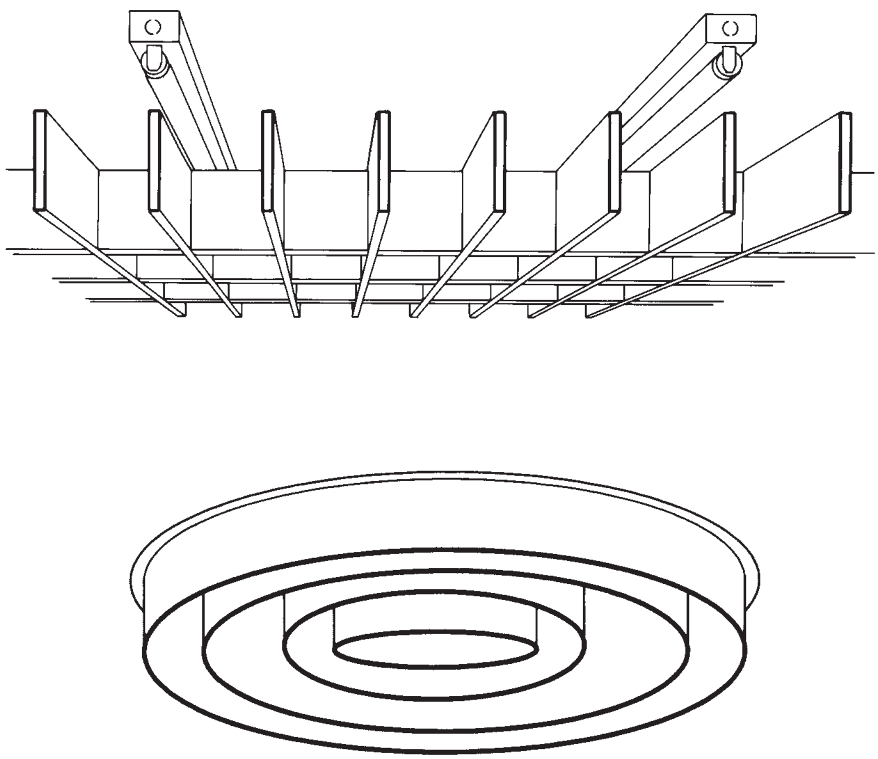


Figure 9.23 Louvers.

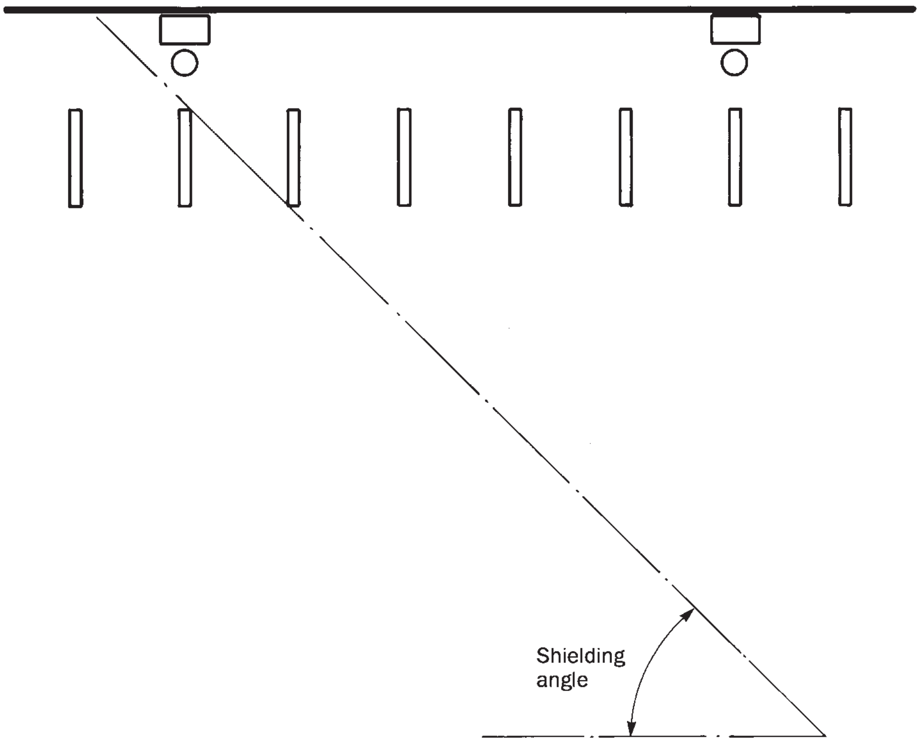
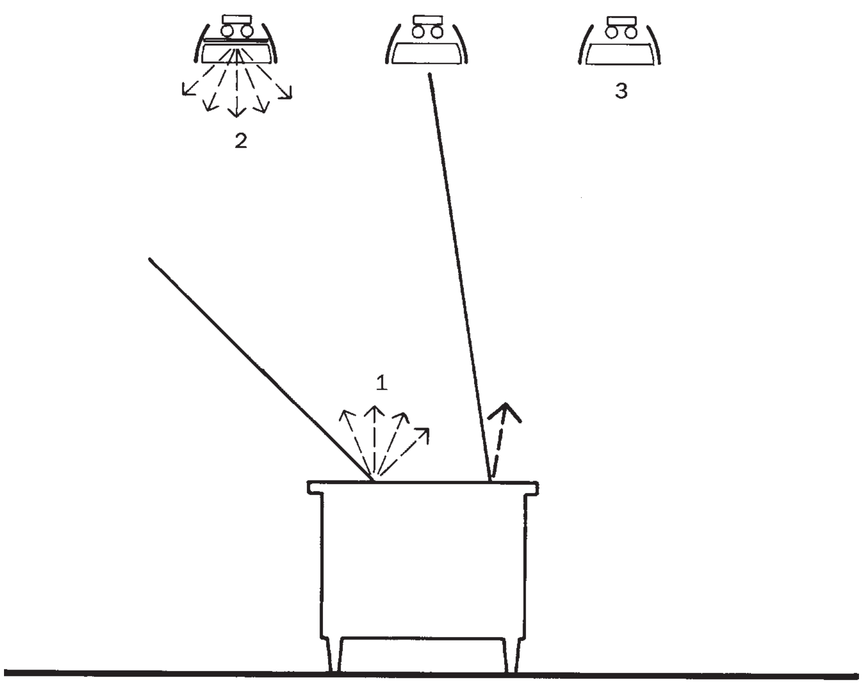


Figure 9.24 Shielding angle.



1. Reduce glossiness of work surface.
2. Add diffuse transmitting material to increase the diffusion of the light source.
3. Locate lighting equipment outside the reflected field of view.

Figure 9.25 Corrective solutions.

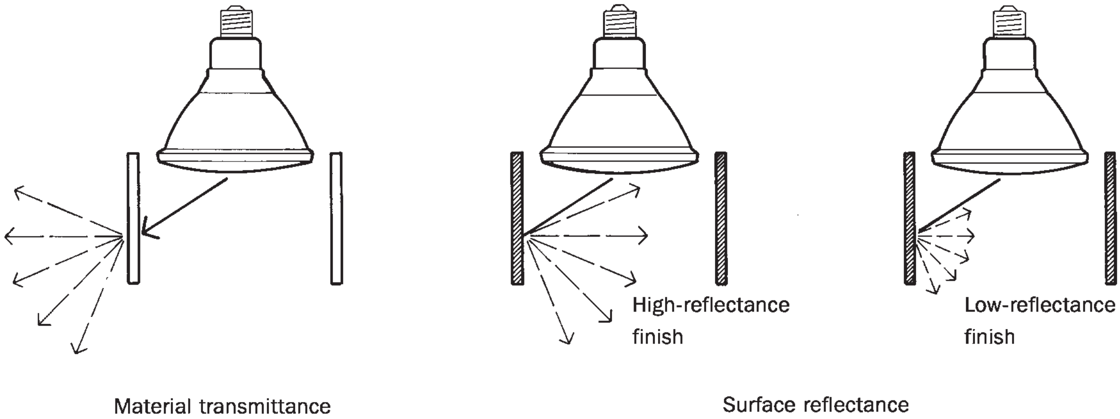


Figure 9.26 Transmitting materials: translucent white and colored plastic or glass, perforated metal. High-reflectance finish: lightly etched metal, light wood, light-colored paint. Low-reflectance finish: matte black finish, dark wood finish, dark-colored paint.

ded into other materials without loss of light from the sides.

Optical fibers are combined in two kinds of bundles: coherent and incoherent. *Coherent bundles* contain fibers that are identically positioned at the point of light entrance and light exit. Because each fiber conducts a portion of the light pattern to the same point on the receiving end of a bundle, images can be transmitted through the bundle. *Incoherent bundles* contain a random arrangement of fibers that can be used to transmit light but not images.

A typical fiber-optic lighting system consists of: (1) a light projector, (2) a tungsten-halogen or metal halide light source, (3) an optical-fiber harness, (4) a fitting for each of the bundles, and (5) the bundles of optical fibers themselves. Silicone rubber sheathing gives the bundles protection without loss of flexibility.

GLARE CONTROL

Sometimes the lens or reflector that is providing the light control is also used to achieve concurrent glare control and lamp concealment. At other times separate elements are used.

Baffles and Louvers

Baffles and louvers shield glare at normal viewing angles, thereby contributing to visual comfort.

Baffles provide shielding in one direction, along a single axis (figure 9.22). For small-aperture luminaires, a baffle around

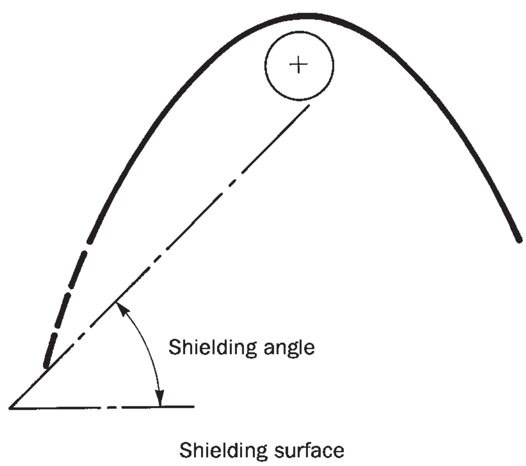


Figure 9.27 Shielding as an aspect of contour design.

the perimeter provides shielding from all directions.

Louvers are a series of baffles or shielding elements placed in a geometric pattern to provide shielding from many directions with minimum interference to the desired beam distribution (figure 9.23).

Shielding conceals the lamp and controls glare within a zone called the *shielding angle*. This is the maximum angle that the eye is raised above horizontal without seeing the light source beyond the shielding system (figure 9.24).

Although baffles and louvers conceal the light source from direct view within this specified zone, horizontal work surfaces are still directly exposed to the source. The mirrored image of the light source becomes a source of *reflected glare* from glossy paper, photographs, objects behind glass, and polished tabletops (figure 9.25).

Baffles and louvers may be black or made from reflective and transmitting materials. The intensity of light directed toward the eye is determined by the luminance of these surfaces. The choice of materials is based on various considerations including visual comfort and design harmony with the space (figure 9.26).

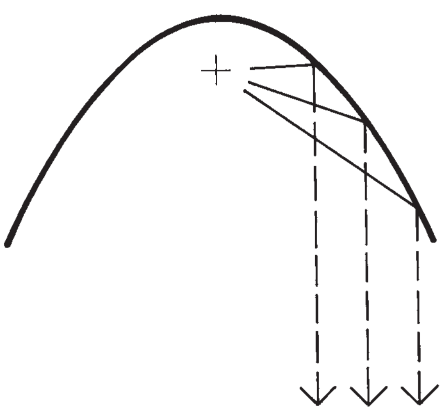
To achieve concurrent glare control and lamp concealment with minimal change in the diffuse beam, use open louvers, or plastic or glass with a slight degree of diffusion. Whether the beam is modified by diffuse reflection or by diffuse transmission, the distribution of light is the same.

Reflectors

An opaque (light-blocking), concave reflector also functions as a baffle, which shields the light source. Additionally, the reflector's shape affects the appearance of the visible interior surface. If light is redirected toward the eye, the result is high luminance and unpleasant direct glare. If light is directed downward and away from the eye, luminance is reduced and glare is avoided.

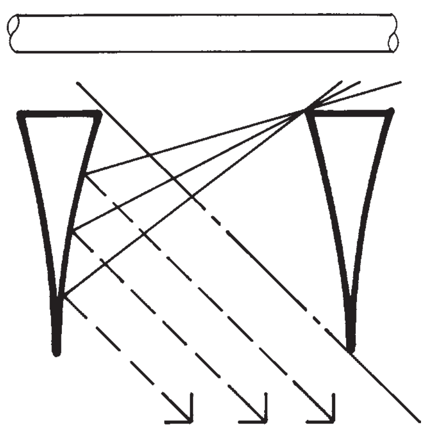
In the most efficient reflector designs, source shielding is incorporated into the contour design. This involves extending the reflector surface to provide the necessary shielding (figure 9.27).

As reflector depth is increased, total efficiency is reduced because of absorption



Reflector action

Figure 9.28 Parabolic reflector used for glare control.



Louvers and baffles

Figure 9.29 Parabolic reflector design for louvers and baffles.

losses at the reflector surface. Because a greater portion of the emitted light is brought under control and redirected, however, candlepower and useful lumens increase.

Parabolic reflectors are often used for glare control. Little reflected luminance occurs in the cross view of these reflectors because most of the light is directed downward with minimal light directed toward the eye; this gives an impression of low brightness from normal angles of view (figure 9.28).

Diffusion of the reflector surface causes more light to be directed toward the eye. As a result, luminance is increased when reflector surfaces are etched or brushed.

Parabolic reflector design is applied to both reflectors and baffles. Figure 9.29 shows the pattern of light reflections for light rays originating above the louver. Ideally, light is reflected at an angle equal to the shielding angle.

Well-designed, specular, parabolic louvers provide equal or superior glare control to matte-black or gray louvers, with greater system efficiency because of the reduced absorption of light.

Photometrics 10

It is impossible to see a footcandle. What is seen is luminance, which is a function of the amount of light falling on a surface and the reflectance of that surface, modified by the surrounding conditions and adaptation of the eyes.

MEASUREMENT OF LIGHT

Photometry is the science that measures light. Five terms are commonly used to quantify light: intensity, flux, illuminance, exitance, and luminance.

1. **Intensity** is the light emitted in a specific direction by a source. Properly called *luminous intensity* and defined as *flux per solid angle in a given direction*, it is measured in candelas (cd). Intensity in a succession of directions is plotted on a distribution curve or polar graph (figure 10.1).

2. **Flux** is the light emitted in all directions by a source. Properly called *luminous flux* and defined as *time rate flow of light*, it is measured in lumens (lm).

3. **Illuminance** is the density of light at any given point on a surface. Properly defined as *density of flux incident on a surface measured perpendicular to the surface*, it is measured in footcandles (fc).

4. **Exitance** is the total quantity of light emitted, reflected, or transmitted in all directions from a surface. Properly defined as *density of flux leaving a surface*, it is measured in lumens per square foot (lm/ft^2).

5. **Luminance** is the accepted term for light that is reflected from a surface in a given direction (back toward the eyes). Properly defined as *intensity of flux leaving a surface in a given direction*, it is measured in candelas per square foot (cd/ft^2).

Measurement Limitations

Illuminance is frequently used to measure the quantity of light in architectural space because it is the easiest and least expensive unit to measure. Yet it is impossible to *see* a footcandle!

What is seen is *luminance*, which is a function of the amount of light falling on a surface and the reflectance of that surface (its ability to reflect light). We see an object or surface only when light is reflected from that object or surface back toward the eyes, or when it is emitting light itself (self-luminous).

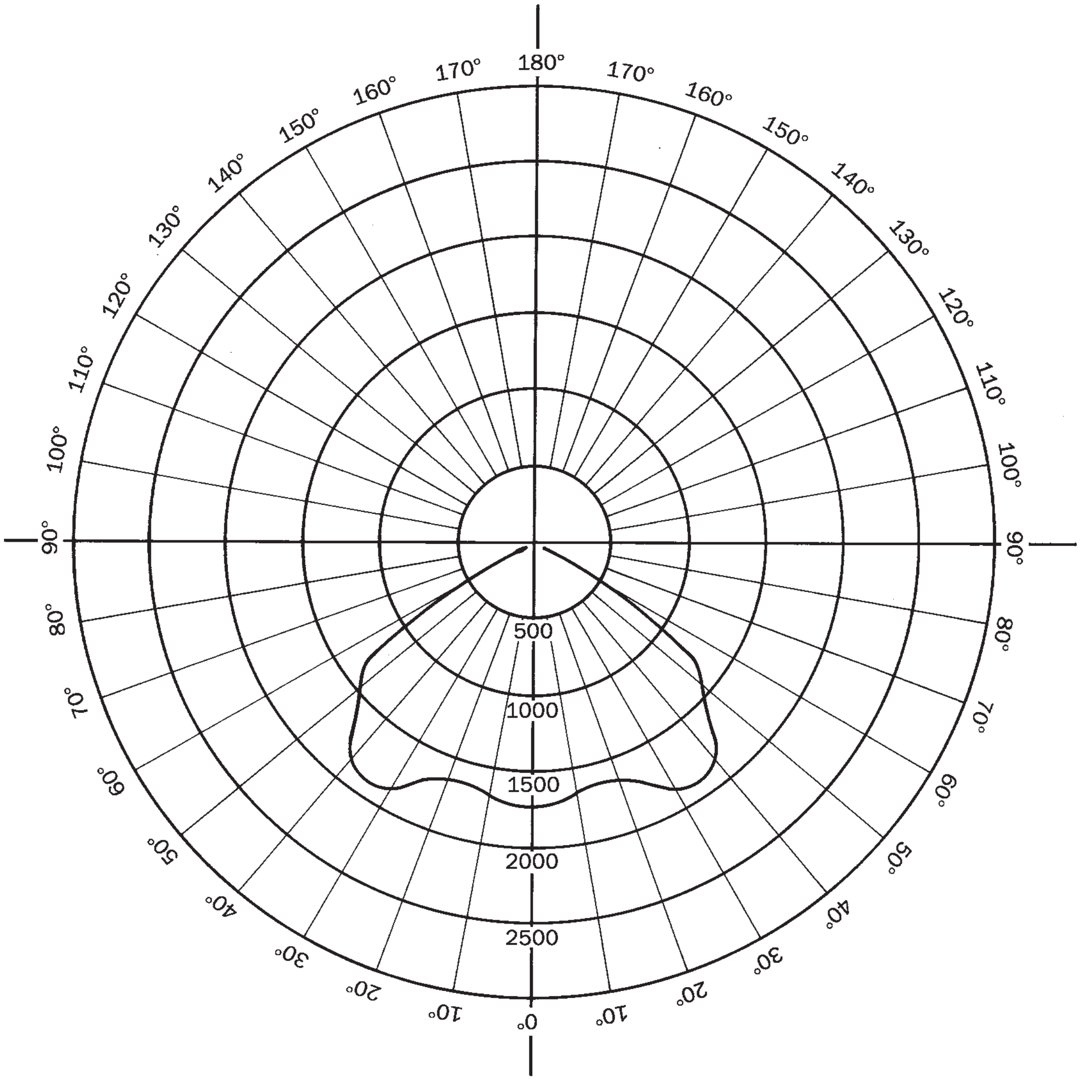


Figure 10.1 Polar luminous intensity distribution curve.

Brightness is what we perceive. It is a subjective attribute perceived in varying degrees of intensity. Reflected light was formerly measured in *footlamberts* (*fL*). Because brightness changes with viewing angle, the term footlamberts has been deprecated by the Illuminating Engineering Society of North America (IESNA). Perceived luminance is now measured by exitance.

It is only meaningful to measure exitance, however, if this quantity remains constant (or nearly so) for a wide range of viewing angles. Diffuse surfaces, called *Lambertian* for the German physicist and philosopher Johann Heinrich Lambert (1728–1777), exhibit this property; thus, it is appropriate to measure exitance only for Lambertian surfaces.

Calculations for illuminance (footcandle values) overlook the aesthetic, psychological, and physiological variables of the human visual process. When a convenient measure of perceived luminance becomes available, it will be more useful to calculate perceived surface luminance values, which account for these factors.

The perception of surface luminance is based largely on the eye's ability to *adapt*. The iris *dilates* (opens) when illuminance is low and *contracts* (closes) when illuminance is high. It takes the eye longer to adapt from light to dark than from dark to light. When you enter a dark theatre on a sunny day, it takes twenty to thirty minutes for the eyes to adapt completely to the lower illuminance. When you leave the theatre and return to daylight, it sometimes takes only seconds for the eyes to adapt to the higher luminance.

In a more subtle way, the eyes are continually adapting as you move in and through variously lighted spaces or look around at objects of varying illuminances. Even measured luminance does not indicate the *apparent* brightness because of the eye's ability to adapt. Measured luminance, then, yields a poor indication of perceived brightness, which is modified by the surrounding conditions and adaptation of the eyes.

It is the *balance* of these relative luminances, not the *quantity of illuminance* received on a surface, that determines successful lighting design. Therefore, the illuminance measurements that follow are *not* to be used as the starting point for a design. They are to be used only for lamp and luminaire selection or to evaluate a lighting design.

Luminous Intensity Distribution Curve

The intensity distribution curve represents the amount of luminous intensity (cd) generated in each direction by a light source in a plane through the center of the source. Consequently, the luminous intensity curve gives a picture of the total light pattern produced by a source.

Luminous intensity distribution curves are available from luminaire manufacturers and are often found on the back of the manufacturer's product data sheet. A *polar graph* is used to represent the distributional intensity of a luminaire, and a *rectilinear* or *Cartesian graph* to represent the distributional intensity of a directional lamp.

In the polar graph (figure 10.1), the luminaire is located at the center of the radiating lines. The radiating lines represent specific degrees of angular rotation from the 0° axis of the luminaire (*nadir*). The concentric circles represent graduating intensity expressed in candelas, with values entered along the vertical scale.

To determine the luminous intensity of this luminaire at 30°, find the appropriate angled line drawn from the center of the luminaire. Follow the line until it meets the polar curve, then follow the circular line originating at that point and read the luminous intensity (in candelas) on the vertical scale. In figure 10.1, the luminaire produces 1,850 cd at 30° from nadir.

For luminaires with symmetrical light distributions, a single curve fully describes the luminaire's distribution. Often only one side of the polar graph is shown, since the other side is an identical, mirror image.

A luminaire with an asymmetrical distribution, such as a linear fluorescent downlight, requires curves in a number of planes to adequately represent its distribution. Typically, one curve is parallel to the luminaire and another is perpendicular to

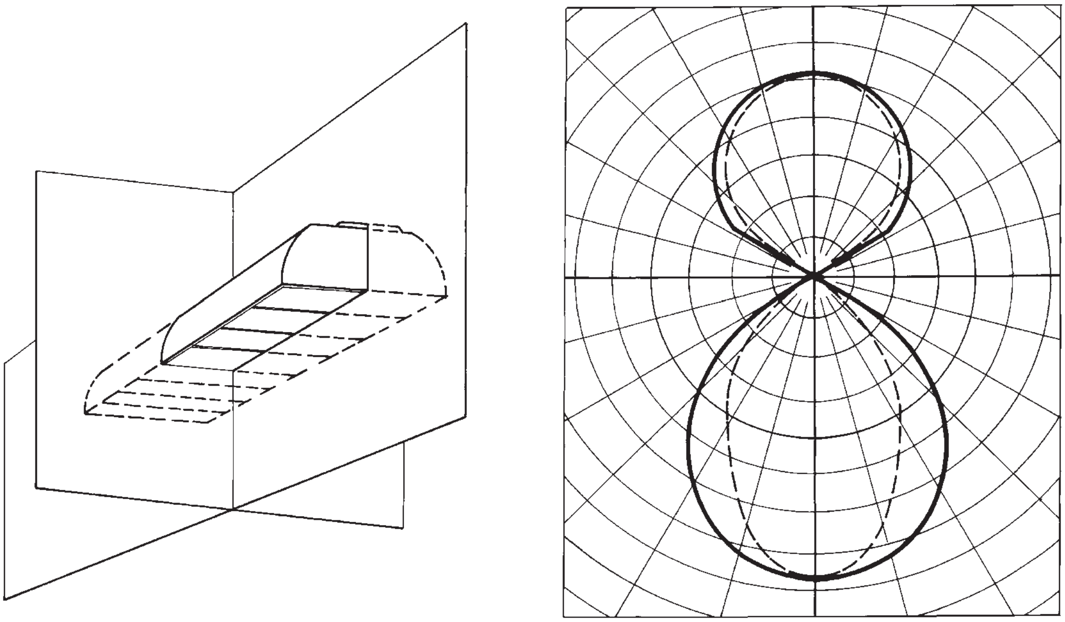


Figure 10.2 Polar graph for a fluorescent luminaire.

the luminaire; sometimes either a third plane at 45° or three planes at 22½° intervals are added (figure 10.2).

Reflector lamp sources or luminaires with directional distributions and abrupt cutoffs, where the light intensity changes rapidly within a small angular area, give values that are difficult to read on a polar graph. Consequently, a rectilinear or Cartesian graph is substituted to portray the candela distribution (figure 10.3).

On this graph, the horizontal scale represents the degrees from the beam axis and the vertical scale represents the intensity in candelas. In the graph on the right of figure 10.3, approximately 3,000 cd are produced by the light source at 10° from the beam center.

When selecting luminaires for a lighting application, be sure that the proposed luminaire *and its source* are precisely those shown in the manufacturer's photometric test data. It is inaccurate to extrapolate from one source or reflector finish to another unless the photometric report includes multipliers for various tested sources and reflector finishes.

RECOMMENDED ILLUMINANCE VALUES

Illuminance value recommendations are published as footcandles (fc) at the *workplane*. For almost all commercial and industrial activities, this surface is considered to be a horizontal plane 2 ft 6 in AFF (above finished floor)—standard desk height—even though the space may be a corridor or a basketball court with no desk in sight.

Remember that these values refer to illuminance on the horizontal work surface only; they have limited significance to us when we interpret the actual environment. Such factors as wall lighting, brightness accents, shadow, sparkle, and color have a greater influence on emotional reaction. These factors are particularly important in areas involving casual seeing where low

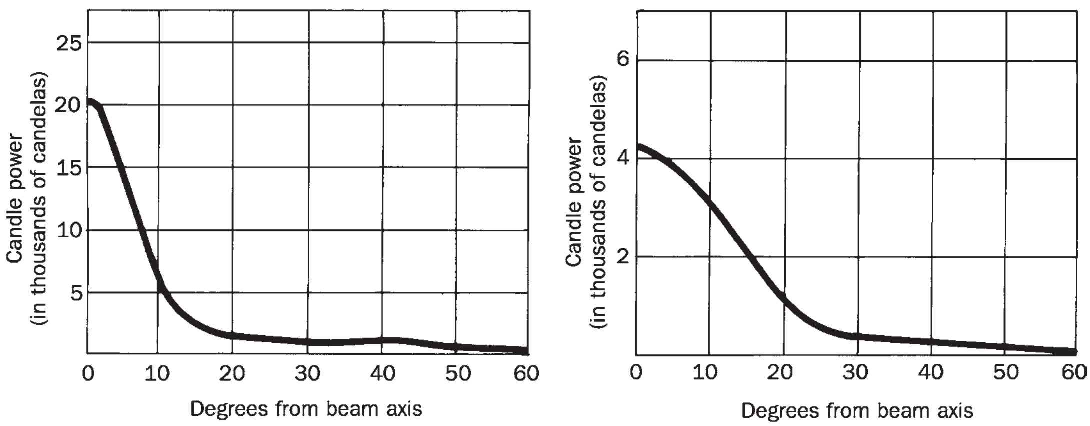


Figure 10.3 Rectilinear luminous intensity distribution curve of a 60PAR38/HIR spot lamp (left) and a 60PAR38/HIR flood lamp (right).

recommended illuminance values may be misleading because a dull or gloomy environment will be unsatisfactory.

True illuminance requirements vary with the visual difficulty of the work task, the age and eyes of the worker, and the importance of speed and accuracy in the completion of the task. Typical illuminance values are shown in table 15 in the Appendix. At best, these values provide a *guide* to the quantity of illuminance needed on the work surface for accurate and comfortable seeing.

In its *Lighting Handbook*, ninth edition, the IESNA publishes an illuminance selection procedure with horizontal illuminance recommendations for specific applications. It is supplemented by a "Design Guide" that attempts to account for other factors that influence perception: including the appearance of the interior, color appearance and color contrast, daylighting integration, glare, vertical illuminance, surface finishes and textures, brightness contrast, facial modeling, and the presence of sparkle.

A consolidated listing of the IESNA horizontal illuminance recommendations appears in table 16 in the Appendix. It covers illuminance values for seven categories and a variety of tasks.

Categories A, B, and C include casual activities that take place over the entire area of a space. For example, in a circulation space such as a hotel lobby or office building corridor, the visual task of circulation is a constant throughout the space, and an illuminance value of 5 fc is recommended.

Categories D, E, and F refer to common tasks that remain fixed at one or more particular locations; these values are to be applied only to the appropriate task area, recognizing that several different kinds of tasks may occur in the same room. The IESNA recommends a value of 20 fc as the minimum illuminance on the horizontal work surface for the "non-task" parts of the room where less demanding visual work is performed.

Category G is for special, visually difficult tasks. The lighting system for these tasks requires careful analysis. Recommended illuminance values are achieved with supplemental task lighting, and range from 300 to 1,000 fc.

Age

IESNA illuminance recommendations do not account for the age of the occupants. The visual requirements of older persons differ from those of younger persons in two ways: (1) the lens of the eye thickens, decreasing the eye's ability to change its shape to properly focus at varying distances (figure 1.6), and (2) pupil size becomes reduced, decreasing the amount of light reaching the retina.

Older persons require higher illuminance values for the same tasks (a sixty-year-old requires three times the illuminance of a twenty-year-old for equal retinal illuminance). At the same time, glare sensitivity within the field of view is significantly increased.

IESNA illuminance recommendations assume an age of forty to fifty-five. As a rule-of-thumb, for persons under age forty, illuminance values may be reduced by up to one-third; for persons over age fifty-five, illuminance values may be increased by up to two-thirds.

ILLUMINANCE CALCULATIONS

Although people see not footcandles but luminance contrast, the question of how much light is necessary for tasks must still be answered. Calculations are performed during the design process to obtain information about lamp and luminaire performance, to evaluate design alternatives, or to refine a particular design.

Following are descriptions of simple calculation methods, with examples for determining illuminance at a specific point and the average illuminance on a specific plane.

Illuminance at a Point

To find the value of incident illuminance at a specific point produced from a compact source, the *inverse-square method* is used. This method closely approximates the illumination where the distance from the source is at least five times the maximum dimension of the source.

Source aimed at a target

Illuminance is proportional to the luminous intensity of the source in the given direction, and inversely proportional to the square of the distance from the source.

To calculate illuminance (fc) from a source aimed at a surface perpendicular to the source:

$$\text{fc} = \frac{I}{D^2}$$

where *I* is the *i*ntensity of the source (in candelas) in the direction of the point and *D* is the *d*istance from the source to the point (figure 10.4).

Example

A 60PAR/HIR/SP10 lamp is aimed at a point on a surface 12 ft away. From a luminous intensity distribution chart (figure 10.3, left), find that the 60PAR/HIR/SP10 lamp produces 20,000 cd at 0°:

$$\text{fc} = \frac{20{,}000}{12^2} = 139$$

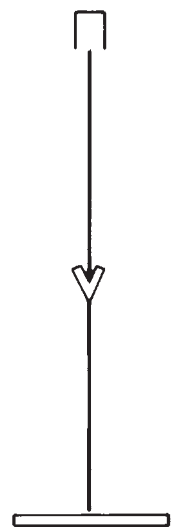


Figure 10.4 Illuminance on a surface perpendicular to the source.

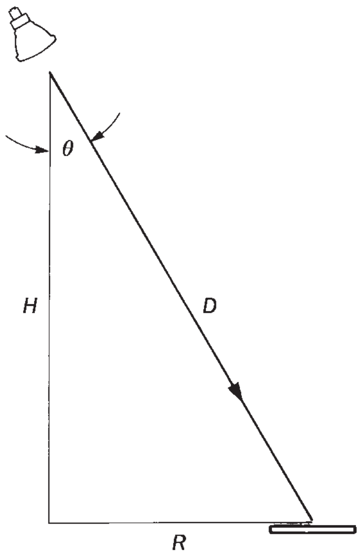


Figure 10.5 Illuminance on a horizontal surface—source at an angle.

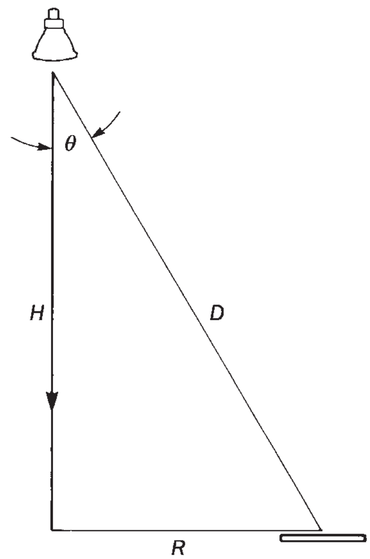


Figure 10.6 Illuminance on a horizontal surface—target located to one side of a source at nadir.

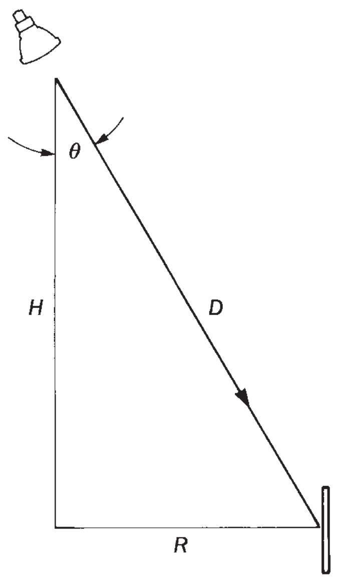


Figure 10.7 Illuminance on a vertical surface—source at an angle.

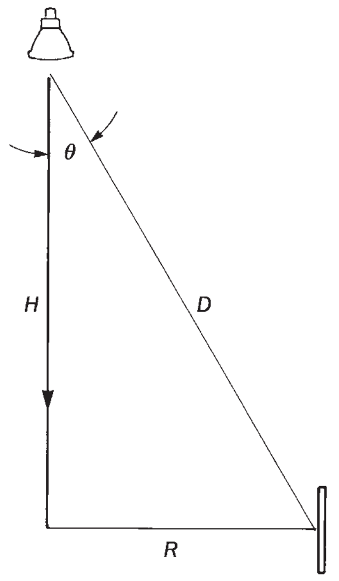


Figure 10.8 Illuminance on a vertical surface—target located to one side of a source at nadir.

Source aimed at an angle to a horizontal surface

If the source is aimed at an angle toward the target instead of being perpendicular to the target, the light will spread over a greater area, reducing the illuminance at a specific point. For a *horizontal* surface, the reduction is equal to the *cosine* of the angle of incidence or "tilt."

To calculate illuminance from a source at an angle to a horizontal surface:

$$\text{fc} = \frac{I}{D^2} \times \cos\theta$$

where *I* is the *i*ntensity of the source (in candelas) in the direction of the light ray, θ is the angle of tilt between nadir and the direction of the light ray, and *D* is the *d*istance from the source to the target surface (figure 10.5).

In figure 10.5, *H* is the vertical mounting *h*eight of the light source above the target of measurement, and *R* is the horizontal distance (*r*un) from the light source to the target.

Example

A 60PAR/HIR/SP10 lamp is tilted at 30° from nadir (straight down) to cast light on a horizontal surface 12 ft away (D). To determine illuminance on the surface, follow these steps:

1. From an intensity distribution chart (figure 10.3, left), find that the 60PAR/HIR/SP10 lamp produces 20,000 cd at 0° (the direction of the ray).

2. From the table of trigonometric functions (table 10 in the Appendix), find that the cosine of 30° is 0.866.

$$\text{fc} = \frac{20{,}000}{12^2} \times 0.866 = 120$$

Source at nadir, target on horizontal surface located to one side

If the source is aimed straight down but the target is located to one side of the central ray, the illuminance at the target on a horizontal surface will be the intensity of the beam at nadir reduced by the cosine of the angle from the source to the target.

To calculate illuminance from a source at nadir to a point located to one side on a horizontal surface, the same formula is used:

$$\text{fc} = \frac{I}{D^2} \times \cos\theta$$

where *I* is the *i*ntensity of the source (in candelas) in the direction of the light ray, θ is the angle between nadir and the direction of the target, and *D* is the *d*istance from the source to the target surface (figure 10.6).

Example

A 60PAR/HIR/FL30 lamp is pointed straight down. To determine the illuminance at a target that is 10° to one side of nadir on a horizontal surface 12 ft away, follow these steps:

1. From an intensity distribution chart (figure 10.3, right), find that the 60PAR/HIR/FL30 lamp produces 2,800 cd at 10° (the direction of the ray).

2. From the table of trigonometric functions (table 10), find that the cosine of 10° is 0.985

$$\text{fc} = \frac{2{,}800}{12^2} \times 0.985 = 19$$

Source aimed at an angle to a vertical surface

If the source is aimed at an angle toward a target on a *vertical* surface, the reduction in illuminance at the target is equal to the *sine* of the angle of incidence or tilt.

$$fc = \frac{I}{D^2} \times \sin\theta$$

where *I* is the *i*ntensity of the source (in candelas) in the direction of the light ray, θ is the angle of tilt between nadir and the direction of the target, and *D* is the *d*istance from the source to the target (figure 10.7).

In figure 10.7, *H* is the vertical mounting *h*eight of the light source above the target and *R* is the horizontal distance (*r*un) from the light source to the target.

Example

A 60PAR/HIR/SP10 lamp is tilted at a 30° from nadir to cast light on a vertical surface 6 ft away. To determine illuminance on the surface, follow these steps:

1. From an intensity distribution chart (figure 10.3, left), find that the 60PAR/HIR/SP10 lamp produces 20,000 cd at 0° (the direction of the ray).
2. From the table of trigonometric functions (table 10), find that the sine of 30° is 0.500

$$fc = \frac{20{,}000}{12^2} \times 0.500 = 69$$

Source at nadir, target on vertical surface located to one side

If the source is aimed straight down but a vertical target is located to one side of the light ray, the illuminance at the target on the vertical surface will be reduced by the sine of the angle between nadir and the target.

To calculate illuminance from a source at nadir to a target located to one side on a vertical surface, the same formula is used:

$$fc = \frac{I}{D^2} \times \sin\theta$$

where *I* is the *i*ntensity of the source (in candelas) in the direction of the light ray, θ is the angle between nadir and the direction of the target (to one side), and *D* is the *d*istance from the source to the target surface (figure 10.8).

Example

A 60PAR/HIR/FL30 lamp is pointed straight down. To determine the illuminance at a target that is 10° to one side of nadir on a vertical surface 12 ft away, follow these steps:

1. From an intensity distribution chart (figure 10.3, right), find that the 60PAR/HIR/FL30 lamp produces 2,800 cd at 10° (the direction of the ray).
2. From the table of trigonometric functions (table 10), find that the sine of 10° is 0.174.

$$fc = \frac{2{,}800}{12^2} \times 0.174 = 3$$

Shortcomings

The inverse-square method yields only a rough idea of what is perceived. Its chief use is for comparison, as when establishing the illuminance ratio between an object and its surround. Even here, the inverse-square method fails to account for any interreflections within the space. And more significantly, perceived brightness depends on the reflectance of the surface and the position of the observer.

Average Illuminance Calculations

To ensure that adequate illuminance is provided over a large area, the *lumen method*, or *zonal-cavity calculation*, is used. This calculation is performed by hand or generated by computer; it predicts the *average* illuminance incident on a horizontal work surface, usually the workplane.

For a rough estimate of the average illuminance on a horizontal surface, the abbreviated version of the lumen method described below will suffice. It considers both the interreflections of light from room surfaces and the contributions of several light sources. It corrects for maintained illuminance, accounting for typical depreciation in lamp lumens over the life of the source and for dirt accumulation on the luminaire surfaces.

This shorthand method is not a substitute for more precise illuminance calculations. It is merely a guide to be used as a quick analysis during the design process.

To calculate the average maintained illuminance falling on a horizontal surface,

$$\text{fc} = \frac{\text{Number of lamps} \times \text{Initial lamp lumens} \times \text{LLF} \times \text{CU}}{\text{Area}}$$

Number of lamps. For single-lamp luminaires, the number of lamps equals the quantity of luminaires in a given area. If the luminaires contain more than one lamp, multiply the number of luminaires by the number of lamps per luminaire.

Initial lamp lumens. The initial lamp lumens are published by the lamp manufacturers in their large-lamp catalogs.

LLF is an abbreviation for *l*ight *l*oss *f*actor. As a system ages, a natural depreciation in light output occurs. (With tungsten-halogen lamps, the loss is negligible.) Also, dust and dirt accumulate on room and luminaire surfaces. Other light loss factors such as ambient temperature, actual input voltage, ballast factor, HID lamp position, and lamp burnouts influence the illuminance in a space; for this quick method, only two are considered: LLD and LDD.

- **LLD** is an abbreviation for *l*amp *l*umen *d*epreciation. This is the amount of light output that is reduced over the life of the lamp because of filament evaporation, tungsten deposits on the bulb wall, and phosphor degradation.

  A list of lamp lumen depreciation for many sources is found in table 11 in the Appendix. When mean lamp lumens (sometimes called "design lumens") are listed in the lamp catalog, this value may be used directly in the formula without the LLD factor.

- **LDD** is an abbreviation for *l*uminaire *d*irt *d*epreciation. This is the reduction of light output over time owing to the accumulation of dust and dirt on the reflecting and transmitting surfaces of the luminaire. This figure is dependent on the cleanliness of the space, the frequency of luminaire cleanings, and the luminaire's tendency to collect dirt (for example, open-top luminaires have a greater ability to collect dirt than closed-top luminaires; some luminaires have a ventilation pattern designed so that the flow of air slows the accumulation of dust). See tables 12 and 13 in the Appendix.

With this method, LLF = LLD × LDD. Typical light loss factors for open light-shielding systems (such as louvers) are 0.85 for very clean spaces, 0.75 for clean spaces, 0.65 for medium spaces, and 0.55 for dirty spaces.

CU stands for *c*oefficient of *u*tilization. The CU is an expression of the percentage of light output that is expected from a specific luminaire in a room. It accounts for the efficiency of the luminaire: its ability to deliver light to the work surface compared to the lumens supplied by the lamp(s). This is the amount of light that is not trapped and lost inside the luminaire.

The CU also accounts for the efficiency of the room in redirecting and interreflecting the incident light that strikes its surfaces. This is affected by the room's proportions as well as its reflectances. A large, low room is more efficient than a tall, narrow one. In the large, low room, little incident light is interrupted by the walls; almost all of the light is received directly by the workplane. In a high, narrow room, much of the incident light strikes the walls at least once before reaching the workplane, sometimes being reflected between several surfaces before reaching the task.

These variables produce an infinite number of CUs for each luminaire. For practical purposes, they are reduced to a group of figures for typical room proportions and reflectances.

Room Cavity Ratio. The CU is found by checking the manufacturer's coefficient-of-utilization table, which is usually published on the back of product data sheets. In order to use the CU table, it is first necessary to calculate the room cavity ratio.

The room cavity ratio provides an expression of the efficiency of room proportions. To determine this ratio:

$$\text{RCR} = \frac{5(h)(l+w)}{l \times w}$$

where h is the *h*eight of the ceiling above the task surface, l is the *l*ength of the room, and w is the *w*idth of the room. The task surface is usually considered to be 2 ft 6 in AFF (*a*bove *f*inished *f*loor) (figure 10.9).

A sample coefficient of utilization table for a compact fluorescent, open-reflector downlight is shown in table 14 in the Appendix.

Example

Calculate the average maintained illuminance on the workplane in a 15 ft × 30 ft

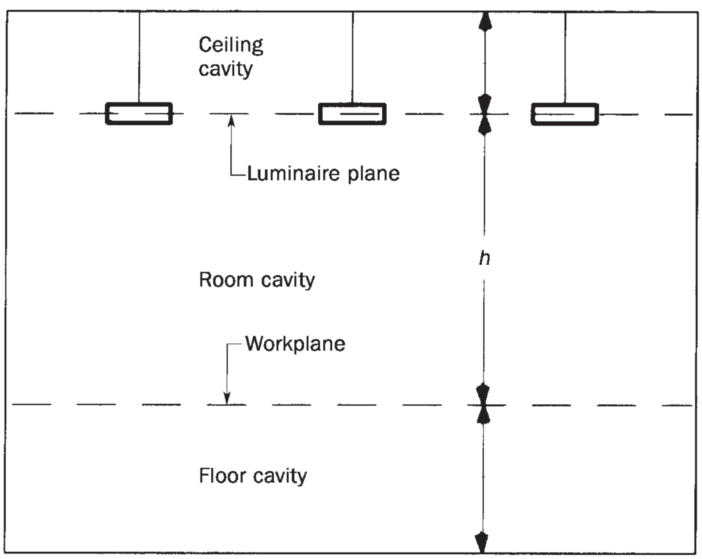


Figure 10.9 The room cavity used in the abbreviated lumen or zonal-cavity method.

office with an 8 ft ceiling and a regular arrangement of eight luminaires; each luminaire uses two 26 W compact fluorescent lamps.

$$\text{fc} = \frac{\text{Number of lamps} \times \text{Initial lamp lumens} \times \text{LLF} \times \text{CU}}{\text{Area}}$$

1. The number of lamps (2 lamps per luminaire × 8 luminaires) is 16.

2. From a large-lamp catalog, find that the initial lumens for a 26 W compact fluorescent lamp are 1,800 lm.

3. LLF = LLD × LDD.
   a. LLD: in table 11, under *fluorescent, compact*, find that the lamp lumen depreciation factor is 0.85.
   b. LDD: in table 12, find that a direct downlight with an opaque, unapertured top enclosure and without a bottom enclosure is maintenance category IV. In table 13, a very clean room that will have its luminaires cleaned every six months yields a luminaire dirt depreciation factor of 0.96.
   c. 0.85 × 0.96 = 0.82.

4. To find the coefficient of utilization, first calculate the room cavity ratio:
   a. h = ceiling height of 8 ft 0 in minus desk height of 2 ft 6 in = 5 ft 6 in (5.5 ft).

$$\text{RCR} = \frac{5(h)(l+w)}{l \times w}$$

$$= \frac{(5)(5.5)(15+30)}{(15)(30)} = 2.75$$

   b. In table 14, which is supplied by the manufacturer of this compact fluorescent, open-reflector downlight, find that for a room with 80% ceiling reflectance, 50% wall reflectance, 20% floor reflectance, and an RCR of 3, the CU is 0.68.

$$\text{fc} = \frac{(16)(1{,}800)(0.82)(0.68)}{(15)(30)} = 36$$

This office, lighted by eight, two-lamp, 26 W, compact fluorescent, open-reflector downlights, will have an average maintained illuminance of 36 fc on the desk. Although the lumen method does not demonstrate it, in all spaces the illuminance value is higher in the center of the room and drops off near the walls because of the absorption of the perimeter surfaces.

Shortcomings

Whether executed by hand or calculated by computer, the lumen method fails to provide the *range* of light intensity in a room and identify *where* differences in illuminance values occur. It is, therefore, inaccurate for nonuniform and task-ambient lighting systems.

This method is also unable to provide information about lighting quality, visual comfort, and luminance patterns. The lumen method is useful mainly for predicting horizontal illuminance with general lighting systems.

Computer Assistance

The complete zonal-cavity method is found in the ninth edition of the IESNA *Lighting Handbook*, Chapter 9, and is available on disc from several software companies for use with a personal computer.

Computer-generated point calculations yield illuminance at selected points throughout a room. They also provide average, maximum, minimum, and standard deviation of illuminance values; room surface luminances; and lighting power density (watts/ft^2). Output is usually a chart of calculated values, an isofootcandle plot, or a shaded plan with gray scales representing the range of illuminance values. This software can model reflections only from perfectly diffuse surfaces, however, although this is adequate for most lighting calculations.

Computer-generated ray-tracing calculations are the most accurate method of computing illuminance. By tracing each "ray" of light, realistic depictions of illuminance patterns on room surfaces, partitions, furniture, and artwork are displayed, including reflection from specular surfaces and refraction by transparent objects. Output is in the form of renderings or video images. Hardware requirements for this kind of program are greater than for other methods; at a minimum, a personal computer with powerful graphics capabilities is necessary.

The IESNA publishes an annual survey of lighting software in its magazine *Lighting Design + Application*. Products are reviewed for analysis features, applications, outputs, user features, hardware requirements, and costs.

SURFACE REFLECTANCE

Although interior surfaces are not light control devices, their reflectance properties are fundamental to the lighting design. The quantity and direction of light reflected from these surfaces affect both the efficiency of the initial light distribution and our perception of surface brightness.

Wall, ceiling, and floor surfaces are large-area "reflectors" that redistribute light in the room. High-reflectance finishes, such as white and off-white, promote maximum use of the available light; increasingly darker finishes intercept and absorb increasingly greater proportions of the light.

Because a useful amount of light reaches the workplane after reflection from the walls and the ceiling, the efficiency of the lighting system depends in part on the reflectance of room surfaces and finishes. This is particularly true of ambient-diffuse and indirect systems, where a large portion of the light is initially directed toward the ceiling or the walls or both.

In task-oriented spaces such as offices, factories, or cafeterias (where the "task" is seeing the food and the people), the following surface reflectances are recommended for the efficient use of light:

20–50%	floor
50–70%	wall
70–90%	ceiling

The illuminance values in tables 15 and 16 in the Appendix presume that commercial reflectances are:

20%	floor
50%	wall
80%	ceiling

and presume that industrial reflectances are:

20%	floor
50%	wall
50%	ceiling

The recommended reflectances for furniture, machinery, partitions, and work surfaces are the following:

25–45%	furniture and machinery
25–50%	work surfaces

Room surface finish reflectances are obtained from the manufacturers of paints, wall coverings, ceiling tiles, floor coverings, furniture, and machinery. The following *room reflectances* are a guide:

white, off-white, gray, light tints of blue or brown	75–90%
medium green, yellow, brown, or gray	30–60%
dark gray, medium blue	10–20%
dark blue, brown, dark green, and many wood finishes	5–10%