

# LIGHTING DESIGN BASICS

MARK KARLEN

JAMES R. BENYA



JOHN WILEY & SONS, INC.



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# PREFACE

This book had its origins several years ago when we were both repeat presenters as part of a series of professional education events across the country over a period of a couple of years. After a few casual meetings over lunch or dinner we discovered we had many interests and points of view in common. Much of that commonality was based on the fact that each of us were deeply involved in our professional lives; Jim as a lighting designer and electrical engineer; and Mark as an architect, interior designer, and educator.

Each of us has spent many years lecturing and teaching architects and designers, and knew the need for design professionals to understand the concepts and basic principles of lighting design. In our experience, too many of those professionals have not had the opportunity to develop that understanding. We believe there is a need for a different kind of lighting design textbook; one that focuses on design, rather than terminology and technology; one that will lead architects and interior designers to work with lighting design in an appropriately professional manner.

Working together has had its logistical difficulties. Jim is based in Portland, Oregon, with an extremely busy nationwide professional practice, as well as a calendar full of lecture engagements at universities and professional conferences. Mark is based at Pratt Institute in Brooklyn, New York, with a full schedule of teaching and administrative duties as Chair of the Interior Design Department, as well as many other professional involvements, including delivering several weekend “STEP” workshops each year for ASID, preparing young designers for taking the NCIDQ exam.

Despite the occasional problems of our bicoastal home bases, and with the marvelously professional and undaunting efforts of John Wiley and Sons’ editorial staff, particularly Amanda Miller, Publisher for Architecture and Design, and Jennifer Ackerman, Technical Project Editor, what follows is the concerted effort of the past couple of years. This book is dedicated to our understanding and loving families, and to all of our students—former, present, and future.

*James R. Benya and Mark Karlen*



# LIGHTING DESIGN BASICS



# Chapter 1 INTRODUCTION

## How to Use This Book

This book is an instructional tool designed to develop the necessary knowledge and skills for solving lighting design problems for typical rooms and spaces. Of equal importance is the development of the necessary knowledge and skills for collaborating with lighting design professionals in solving problems for complex rooms and spaces. The book is directed to both students and professionals in architecture and interior design as well as those in related fields such as facilities management, construction management, store planning, and electrical engineering.

The primary focus is on design, not on technology or terminology. *Design* is here defined as the development of a lighting design concept and the selection and placement of luminaires to achieve the desired result. Lighting technology (and related terminology) will be covered in enough depth to serve the design orientation of the book's methodologies. For more information related to these technical factors, the Bibliography identifies the best sources.

This is a how-to instructional textbook, the goal of which is to provide its users with the tools of lighting design required to function effectively in the many design and construction fields of which lighting is an essential part.

### ORGANIZATION

Beyond this introductory chapter, *Lighting Design Basics* is organized in four parts, plus Appendixes and a Bibliography. Here is a description of these parts.

**Part I: *Basics About Lighting*.** Chapters 2 through 6 provide background for the technical (and related terminology) aspects of lighting design—enough to serve this book's purpose but without unnecessary emphasis on technical issues. More specifically, the technical factors addressed are light sources (and their color implications), luminaires, switching and controls, daylighting, and calculations (including rule-of-thumb techniques).

**Part II: *Design Process*.** Chapters 7 through 9 provide a basic approach or methodology for developing successful lighting design concepts and solutions, including the graphic representation tools and techniques used to convey the solutions. In this context, success is defined as meeting functional visual requirements, achieving satisfying aesthetic results, and using lighting design technology (including code compliance) intelligently.

**Part III: *Applications and Case Studies*.** Chapters 10 through 15 focus on the typical lighting design problems encountered in the five major building use

## 2 LIGHTING DESIGN BASICS

types: (1) residential, (2) office/corporate, (3) hospitality/foodservice, (4) institutional/health care, and (5) retail store. Case studies are provided for many of the typical rooms and spaces found in these building use types. This is the heart of the book, where design problems, their solutions, and the rationales for the solutions are presented in detail.

**Part IV: Professional Skills.** Chapters 16 through 18 provide additional and necessary information about functioning as a designer or design-related professional in matters concerning lighting design. They are intended to serve as a transition from learning to professional practice.

### **Appendixes**

Appendix A is a brief overview of lighting design for the exterior of buildings and exterior spaces. This specialized aspect of lighting design is complex and requires an extensive study of its own. This Appendix provides a starting point and direction for those interested in pursuing the subject more fully.

Appendix B is a summary of energy codes and how they affect design. Included are Internet references for obtaining the most recent energy code information within the United States.

### **GETTING THE MOST OUT OF THIS BOOK**

This book is meant to be worked with, not just read. Doing the exercises after reading and understanding the related case studies is the heart of the learning process presented here.

The case study examples and the exercises represent typical lighting design applications. Beyond these examples, lighting design becomes increasingly complex and challenging, even for the most knowledgeable and experienced professionals. The purpose here is not to prepare the reader for those complex problems but rather to provide understanding of lighting design concepts, techniques, and realistic goals so collaboration with a lighting design professional can achieve the best possible results. One must learn to commu-

nicate design intentions in a way that a lighting designer can use. Those communication skills require a conceptual understanding of lighting design, the acquisition of which should be one of the major learning goals in working with this book.

Many technical aspects of lighting design go considerably beyond the scope of this book. Issues such as the fine points of color rendition, code compliance, project budget, and lighting live performance spaces can be extremely complex. Working knowledge of these factors is not expected of broad-based design and built environment professionals. However, general familiarity is required to collaborate productively with lighting designers. To acquire deeper knowledge in these technical matters, consult the Bibliography.

In a classroom setting, the value of this book is enhanced by an exchange of ideas among students working on the same exercises as well as the instructor's critiques and open classroom critiques and discussion. Beyond the classroom, one should take advantage of every opportunity to discuss exercise solutions with design professionals, particularly those with extensive practical experience. Such discussion can be invaluable.

Two readily available learning tools should be used concurrently with this book. First is the deliberate observation and critique of existing lighting design applications. Be aware of the lighting in public and semipublic spaces, making note of lamp and luminaire types—and, more important, what works well and what doesn't. A great deal can be learned from the successes and failures of others. Second, many architecture and interior design professional publications present enough programmatic, plan, and spatial information about interesting spaces that one can use them as additional exercises for enhancing one's skills.

It all begins with working on paper or the computer and trying a variety of lighting design solutions to typical design problems.

While this book prescribes a particular approach to solving lighting design problems, it should be understood that several potentially successful methodologies exist. In the professional community of lighting designers and the other design professionals who work with them, the problem-solving process enjoys many workable variations. It is expected that individual professionals, after repeated experience with actual problems, will gradually develop a personalized methodology.

# Chapter 2 LIGHT SOURCES

Light occurs in nature, and sunlight, moonlight, and starlight are the most important sources of light to life. But because of their need for additional light, humans have learned to create light as well. Understanding the fundamental difference between natural and man-made light is the beginning of understanding light sources.

Natural light sources occur within nature and are beyond the control of people. These include sunlight, moonlight, starlight, various plant and animal sources, radioluminescence, and, of course, fire.

Man-made light sources can be controlled by people, more or less when and in the amount wanted. These include wood flame, oil flame, gas flame, electric lamps, photochemical reactions, and various reactions, such as explosives.

Due to their obvious advantages in terms of availability, safety, cleanliness, and remote energy generation, electric lamps have displaced almost all other man-made sources for lighting of the built environment. However, because man-made sources consume natural resources, natural light sources should be used to the greatest extent possible. Exploiting natural light sources remains one of the biggest challenges to architects and designers.

## QUALITIES OF LIGHT SOURCES

In practical terms, light sources can be discussed in terms of the qualities of the light they produce. These qualities are critical to the result and must be understood when choosing the source for a lighting plan.

### How Light Is Generated

Most natural light comes from the sun, including moonlight. Its origin makes it completely clean, and it consumes no natural resources. But man-made sources generally require consumption of resources, such as fossil fuels, to convert stored energy into light energy. Electric lighting is superior to flame sources because the combustion of wood, gas, and oil produces pollution within the space being illuminated. Moreover, electricity can be generated from natural, nondepletable sources of energy, including the energy generated by wind, hydro, geothermal, and solar sources.



**Edison Lamp**

How an electric lamp operates determines virtually everything about the light created by it. The common incandescent lamp generates light through the principle of incandescence, in which a metal is heated until it glows. Most other lamps, however, generate light by means of a complex chemical system in which electric energy is turned into light energy where heat is a side effect. These processes are usually much more efficient than incandescence—at the cost of complexity and other limitations. For instance, a fluorescent lamp generates light by a discharge of energy into a gas, which in turn emits ultraviolet radiation, which is finally converted to visible light by minerals that “fluoresce.” This process generates light about 400 percent more efficiently than incandescence and is the reason fluorescent lamps are promoted as environmentally friendly.

## The Spectrum of Light

The spectrum of light is seen in a rainbow or from a prism, and it includes all of the visible colors. We tend to organize color into three primaries (red, green, and blue) and three secondaries (yellow, cyan, and magenta). When primaries of light are combined, the human eye sees white light

Historically, using a filter to remove colors from white light generated colored light. Blue light, for instance, is white light with green, and red removed. Filtered light is still common in theatrical and architectural lighting.

However, most nonincandescent light sources tend to create specific colors of light. Modern fluorescent lamps, for example, create prime colors of light (red, green, and blue) that appear to the human eye as white light. Other lamps, such as low-pressure sodium lamps, create monochromatic yellow light. While most lamps are intended to appear as white as possible, in some cases lamps are designed to create specific colors, such as green or blue.

However, the intent of most light sources is to produce white light, of whose appearance there are two measures:

1. *Color temperature*, which describes whether the light appears warm (reddish), neutral, or cool (bluish). The term *temperature* relates to the light emitted from a metal object heated to the point of incandescence. For instance, the color temperature of an incandescent lamp is about 2700K, appearing like a metal object heated to 2700° Kelvin (2427° Celsius or 4400° Fahrenheit).
2. *Color rendering index (CRI)*, which describes the quality of the light on a scale of 0 (horrible) to 100 (perfect).

All white light sources can be evaluated by color temperature and CRI. Color temperature is the more obvious measure; two light sources of the same color temperature but different CRI appear much more alike than do two light sources of similar CRI but different color temperature.

Natural light is generally defined as having a CRI of 100 (perfect). Color temperature, however, varies a great deal due to weather, season, air pollution, and viewing angle. For instance, the combination of sun and blue skylight on a summer day at noon is about 5500K, but if the sun is shielded, the color of the blue skylight is over 10,000K. The rising and setting sunlight in clear weather can be as low as 1800K (very reddish). Cloudy day skylight is around 6500K.

When choosing electric light sources, it is generally best to select source color temperature and CRI according to the following table. Note that even if daylight enters the space, it is usually not a good idea to try to match daylight with electric light, as daylight varies considerably.



### Color Classification of Light Sources

Color Temperature (Kelvins or K)	Applications
2500	Bulk industrial and security High Pressure Sodium (HPS) lighting.
2700–3000	Low light levels in most spaces [10 foot candles (FC)]. General residential lighting. Hotels, fine dining and family restaurants, theme parks.
2950–3500	Display lighting in retail and galleries; feature lighting.
3500–4100	General lighting in offices, schools, stores, industry, medicine; display lighting; sports lighting.
4100–5000	Special-application lighting where color discrimination is very important; uncommon for general lighting.
5000–7500	Special-application lighting where color discrimination is critical; uncommon for general lighting.
Minimum Lamp CRI	Applications
50	Noncritical industrial, storage, and security lighting.
50–70	Industrial and general illumination where color is not important.
70–79	Most office, retail, school, medical, and other work and recreational spaces.
80–89	Retail, work, and residential spaces where color quality is important.
90–100	Retail and work spaces where color rendering is critical.

### Point Source, Line Source, or Area Source

Light sources vary in shape. The three basic shape types are point sources, line sources, and area sources. Each radiates light differently, thus causing distinctive effects.

### Ballast or Transformer

In order to operate correctly, many electric light sources require an auxiliary electric device, such as a transformer or ballast. This device is often physically large and unattractive and can create an audible hum or buzz when operating.

### Lamp Size

The physical size of the lamp affects the size of the luminaire and, in turn, determines how some sources might be used. Small, low-wattage lamps permit

small luminaires, such as undercabinet lights and reading lights; large, high-powered lamps, such as metal halide stadium lamps, require a large luminaire, both for heat and for the reflector needed to aim the light properly.

### Voltage

The electric power needed to operate a lamp is measured first by voltage. In the United States, the standard voltage services are 120 volts, 240 volts, 277 volts, and 480 volts. The standard 120-volt service is available in all building types; 240-, 277-, and 480-volt services are available only in large industrial and commercial buildings. Service voltage varies from country to country.

Many types of low-voltage lamps, operating at 6, 12, or 24 volts, are used throughout the world. Transformers are used to alter the service voltage to match the lamp voltage.

### Bulb Temperature

The bulb of a lamp can get quite hot. The bulb temperature of incandescent and halogen lamps and most high-intensity discharge (HID) lamps is sufficiently high to cause burns and, in the case of halogen lamps, extremely severe burns and fires. Fluorescent lamps, while warm, are generally not too hot to touch when operating, although contact is not advised.

### Operating Temperature

Fluorescent lamps are sensitive to temperature caused by the ambient air. If the bulb of the lamp is too cool or too hot, the lamp will give off less light than when operated at its design temperature. Most other lamps give off the same amount of light at the temperatures encountered in normal applications.

### Operating Position

Some lamps produce more light or have longer lamp life when operated in specific positions with respect to gravity. Metal halide lamps are especially sensitive; some versions will not operate unless in the specified position.

### Starting, Warming Up, and Restarting

Some lamps, especially incandescent, start operating as soon as power is applied, but most other types, especially discharge lamps, like fluorescent and metal halide lamps, require the lamp to be started by a high-energy pulse. The

lamp warms up gradually, first glowing faintly and then, after a modest period, giving off full light. If then extinguished, fluorescent lamps can be restarted right away, but most HID lamps, like metal halide lamps, must cool considerably before restarting, potentially causing several minutes of unwanted darkness. Obviously, these considerations can dramatically affect design when safety or security might be compromised by a long warm-up or restart time.

### Dimming Characteristics

Dimming is the process by which lamps are operated at less than full light, often as an energy-saving or mood-creating method. With incandescent lamps, dimming is simple and inexpensive, but with other types, dimming can be considerably more complex, and, in some cases, not advisable.

### Energy Efficiency

The energy efficiency of a light source is called its *efficacy* and is measured in lumens per watt. Like miles per gallon, the higher the number, the better. Low-*efficacy* lamps, like incandescent lamps, are less than 20 lumens per watt. Among good colored light sources, metal halide and fluorescent lamps can achieve up to about 100 lumens per watt; distorted color sources, like low-pressure sodium lamps, presently achieve almost 180 lumens per watt.

## INCANDESCENT AND HALOGEN LAMPS

Incandescent lamps generate light when electric current heats the lamp's filament. The hotter the filament, the whiter the light. The problem is that as the lamp filament gets hotter, the more rapid the evaporation of metal from the filament. A very dim lamp giving off yellow-orange light (2200K) may last a long time; a lamp giving off pure white (5000K) light will probably last for a few seconds only. The evaporated filament material blackens the bulb wall.

*Standard incandescent lamps* today use tungsten filaments that generate a warm-colored white light and last about 750 to 1000 hours. Two special types of incandescent lamps—krypton-incandescent lamps and xenon-incandescent lamps—make lamps last a bit longer. The temperature of the incandescent lamp bulb is generally too hot to touch but luminaires are designed to prevent inadvertent contact, so in general, the lamp's heat is not a problem. The color temperature of incandescent lamps is about 2700K, generating a warm-toned light.



Incandescent Lamps

*Tungsten-halogen lamps* (also called *TH* or simply *halogen* lamps) give off whiter light and last longer than standard incandescent lamps. Lamp life for halogen lamps ranges from 2000 hours up to 10,000 hours. Some types of halogen lamps use a quartz glass bulb and get extremely hot, requiring special protection for safety. The color temperature of halogen lamps is about 3000K, making their light appear slightly whiter and cooler than incandescent.

*Low-voltage* incandescent and tungsten-halogen lamps are smaller than regular lamps, a trait that has numerous advantages for accenting and display. Low-voltage lighting is particularly popular for specialty lights and for display lighting in retail, museums, homes, and other applications. For instance, most popular do-it-yourself landscape lighting is low-voltage. Transformers are needed to change the primary power, usually 120 volts, to the low voltage. The most common systems are 12 volts; these are used to power the popular MR16 and PAR36 display lamps. Some transformers are part of the luminaire, while in other applications a remote transformer can power a lighting system consisting of many lamps.



**Halogen Lamps**

### **Points to Remember About Incandescent and Halogen Lamps**

Incandescent and halogen lamps operate in virtually any position. They start and warm up almost instantly and can be extinguished and restarted at will. Incandescent and halogen lamps can be dimmed easily and inexpensively. Dimming generally extends lamp life significantly.

Incandescent lamps are among the least energy-efficient sources available. Standard incandescent lamps generate between 5 and 20 lumens per watt; halogen lamps generate between 15 and 25 lumens per watt. The most efficient incandescent light sources are the latest infrared-reflecting halogen lamps, which generate between 20 and 35 lumens per watt.

Designers tend to prefer incandescent and halogen lamps for their color and versatility. When dimming, incandescent lamps are the only type that shifts color toward red as intensity decreases. While other source types have

some size and shape versatility, no source other than incandescent can range from 1/2-watt peanut lamps to 10,000-watt stage lamps. However, their inefficiency and short life are critical drawbacks that must be resolved in the design.

### **Most Common Applications**

Standard incandescent lamps, such as A and R lamps, are still commonly used in residences, hotels and motels, and some retail environments where a residential-like quality is desired. In these applications, the designer is trading the low energy efficiency and short life of the incandescent lamp for its warm color and low costs.

Halogen PAR lamps are commonly used in residential downlighting and outdoor lighting, hotels and motels, and especially in retail display. IR/HIR lamps, the most common display light source in service, are used in recessed lighting, track lighting, and other lampholders in stores of all types.

MR16 and PAR (Parabolic Aluminized Reflector Lamp) low-voltage lamps are commonly used in museums and galleries, residences, landscape lighting, and other applications where a modest amount of light and excellent beam control are called for. Other types of low-voltage lighting are used in residential and hospitality lighting for details and special effects like cove lights and illumination inside and under cabinets.

### **FLUORESCENT LAMPS**

The fluorescent lamp is the workhorse light source for commercial and institutional buildings. Fluorescent lamps use the principle of *fluorescence*, in which minerals exposed to ultraviolet light are caused to glow. Electric energy excites the gas inside the lamp, which generates ultraviolet light. The ultraviolet light in turn excites the phosphors, which are a mixture of minerals painted onto the inside of the bulb. Phosphors are designed to radiate particular colors of white light, thus enabling the choice of both the color temperature and CRI of a lamp. The color of the lamp is described by the name or designation. Traditional lamp colors include *cool white*, *warm white*, and *daylight*. However, modern lamps are identified by a color "name" that designates its color temperature and CRI. For example, a lamp having a color temperature of 3500K and a CRI between 80 and 90 is known as the color 835.

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A fluorescent lamp requires a *ballast* in order to work properly. A ballast is an electrical component that starts the lamp and regulates the electric power flow to the lamp. Some ballasts can operate up to four lamps. There are two types, *magnetic* and *electronic*, of which the latter is generally more energy-efficient and quieter, and it reduces lamp flicker considerably.

Fluorescent lamps can be dimmed through the use of an electronic dimming ballast. Most electronic dimming ballasts require specific dimmers. Dimming range is typically 10 to 100 percent of light or better, with the best ballasts allowing a dimming range of 0.5 to 100 percent. Fluorescent lamps change color slightly when dimmed; their light tends to appear more purple at lower output levels.

Fluorescent lamps are sensitive to temperature. Bulb temperature is critical for proper light output, and lamps operated in very cold or very warm situations generally do not give off as much light as when operated at room temperature. Also, lamps may not start if they are too cold. The minimum starting temperature of a lamp depends on the ballast; minimum starting temperature ratings are available for ballasts to help choose the right type. Most fluorescent lamps get warm, but a person can touch one in operation without being burned.

### Standard Straight and U-bent Lamps

Most common fluorescent lamps are straight tubes. The longest standard fluorescent lamps are 8' long and the shortest are 4". The most common length is 4', and the most common diameters are  $\frac{5}{8}$ " (T-5), 1" (T-8), and  $1\frac{1}{2}$ " (T-12). U-bent lamps are straight lamps that are manufactured in a U shape but otherwise perform about the same as straight lamps.

Standard straight and U-bent lamps are preferred for general illumination because of their cost effectiveness and energy efficiency. In current designs, the T-8 is the most commonly used general-purpose lamp, and the T-5 and T-5 high-output lamps are becoming increasingly popular for a number of specific lighting systems. The T-12 lamps are an older style that is less energy efficient.

### Compact Fluorescent Lamps

There are two major types of compact fluorescent lamps: those with screw bases, designed to directly replace incandescent lamps in incandescent lamp sockets, and those with plug-in bases designed to fit into sockets in luminaires designed specifically for compact fluorescent lamps.

Because compact fluorescent lamps, like all fluorescent lamps, require a ballast, lamps with screw bases are larger and costlier than those for dedicated



Flourescent Lamps



Compact Flourescent Lamps

compact fluorescent luminaires. As a result, it is generally best to employ dedicated compact fluorescent luminaires in new designs. Screw-based compact fluorescent lamps should be used to convert incandescent type luminaires only after the fact.

### Points to Remember About Fluorescent Lamps

Fluorescent and compact fluorescent lamps provide good energy efficiency, good to excellent color, dimming, and many other features expected of modern light sources. Improvements in fluorescent lighting since 1980 now make it useful in homes, businesses, and for almost every other type of lighting application.

The challenge of the designer remains to determine the best light source to meet the user's expectations, and fluorescent lighting is still not a *direct* replacement for incandescent lighting. Fluorescent and compact fluorescent lamps can be used in many places, however, and it is important to develop expertise in using these energy-efficient sources.

## HID LAMPS

High-intensity discharge (HID) lamps are designed to emit a great deal of light from a compact, long-life light source. They are most often used for street and parking lot lighting and for large indoor spaces like gymnasiums and industrial work floors. Most HID lamps approximate a *point source* of light, making them excellent sources for spot lighting equipment such as track lights, display lights, and even stadium lights. HID lamps are generally energy efficient, producing 50 to 100 lumens per watt.

As in fluorescent lamps, a ballast regulates the amount of power flowing into HID lamps. Magnetic ballasts are generally used for most HID lamps, although electronic ballasts are becoming increasingly popular. Ballasts can be bulky, heavy, and noisy, but some types can be mounted remotely from the luminaire.

HID lamps can get quite hot and generally should be protected from direct touch. In addition, some metal halide lamps must be totally enclosed due to a small possibility of lamp explosion. HID lamps start and operate over a relatively wide temperature range, and they are well suited to both indoor and outdoor applications.

HID lamps require time to warm up; they get progressively brighter over several minutes until reaching full light output. The lamp's true light output and color is often not reached for two to five minutes. If power to an operating HID

lamp is interrupted, the lamp must cool before the ignition circuit can restart it. The cool-off period is called the *restrike time*. Some HID lamps must cool more than 10 minutes after being extinguished before they can restrike and warm back up.

### Types of HID Lamps

#### **Metal Halide Lamps**

Metal halide lamps produce white light of a good color quality and are available in many sizes, from compact lamps that can be used in track lighting and table lamps to huge lamps for lighting stadiums. Standard metal halide lamps tend to have a color temperature of 3700 to 4100K and appear cool and slight-



**Metal Halide Lamps**