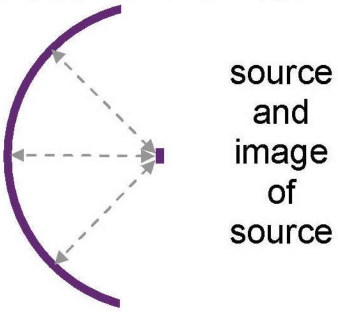
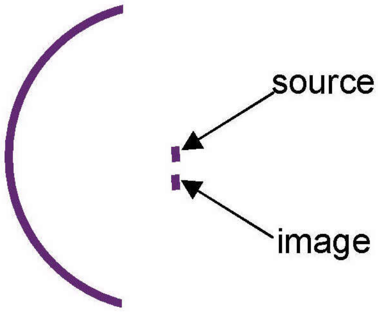
Spherical Reflector

The light emitted from a source in the direction away from the optical system can be redirected toward the optical system by using a **spherical mirror** with the source located at the center of curvature.



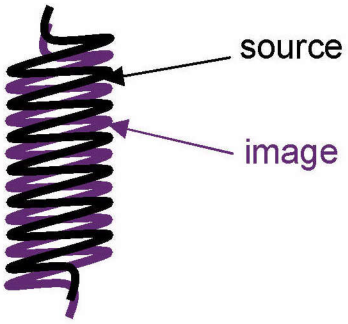
If the source is solid, it is necessary to place the source slightly away from the center of curvature and the image just above, below, or alongside the physical source.



Ignoring losses on reflection, the image has the same radiance as the source, but the effective source area (source plus image) is doubled.

Sometimes this technique is used to place the image of a source in a location where the physical source itself could not fit because of an obstruction such as a lamp envelope or socket.

If the source is not solid, such as a coiled wire tungsten filament, imaging the source almost directly onto itself can help fill in the area between the coils.

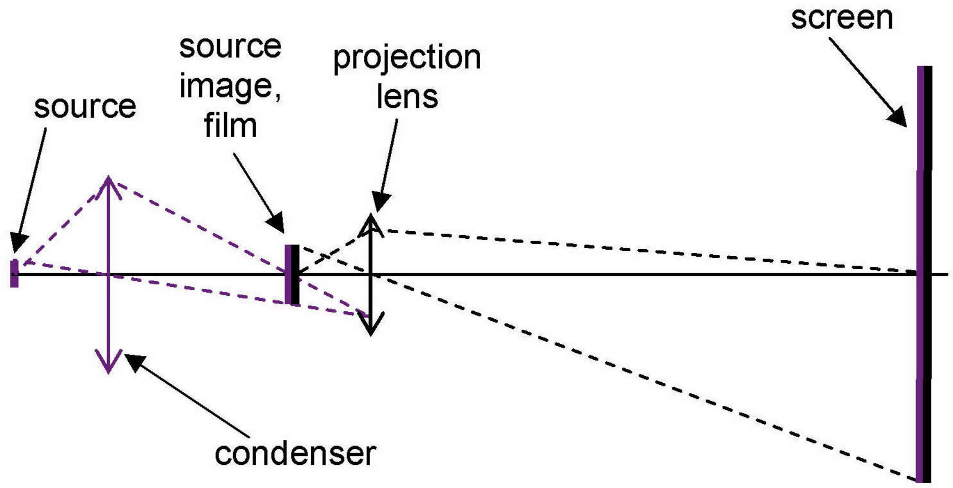


In this case, the effective area of the source is not appreciably increased, but the apparent radiance is nearly doubled.

Abbe Illumination

Abbe illumination is characterized by imaging the source (or imaging an image of the source) directly onto the illuminated area. Since the uniformity of illumination is directly related to the uniformity of source radiance, Abbe illumination requires an extended source of uniform radiance such as a well-controlled arc, a ribbon filament lamp, the output of a clad rod, a frosted bulb, an illuminated diffuser, or the output of an integrating sphere.

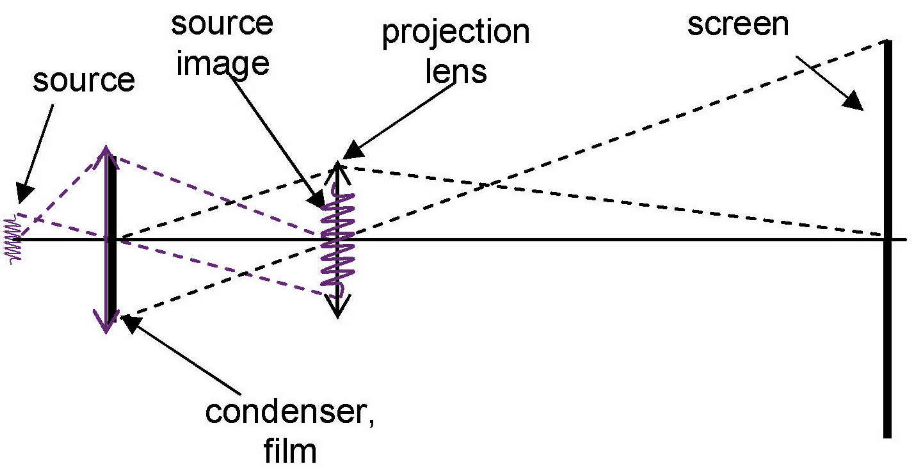
The paraxial layout below shows Abbe illumination used in a projection system. The source is imaged by a condenser onto the film. The projection objective images the film and the image of the source onto the screen. The purple dotted lines show the marginal and chief rays from the source. The black dotted lines show the marginal and chief rays from the film (and the image of the source). The marginal rays go through the on-axis points on the object and image and on the edges of the pupils (which are the lenses in this case). The chief rays go through the edges of the object and image and the on-axis points of the pupils.



Köhler Illumination

Köhler illumination is used when the source is not uniform, such as a coiled tungsten filament. Köhler illumination is characterized by imaging the source through the film onto the projection lens. The film is placed adjacent to the condenser, where the illumination is quite uniform, provided the source has a relative uniform angular distribution of intensity.

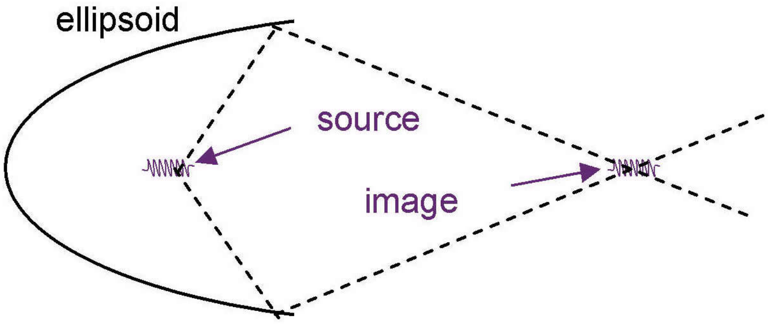
The paraxial layout below shows Köhler illumination used in a projection system. The source is imaged by a condenser onto the projection lens. The projection objective images the film onto the screen. The purple dotted lines show the marginal and chief rays from the source. The black dotted lines show the marginal and chief rays from the film.



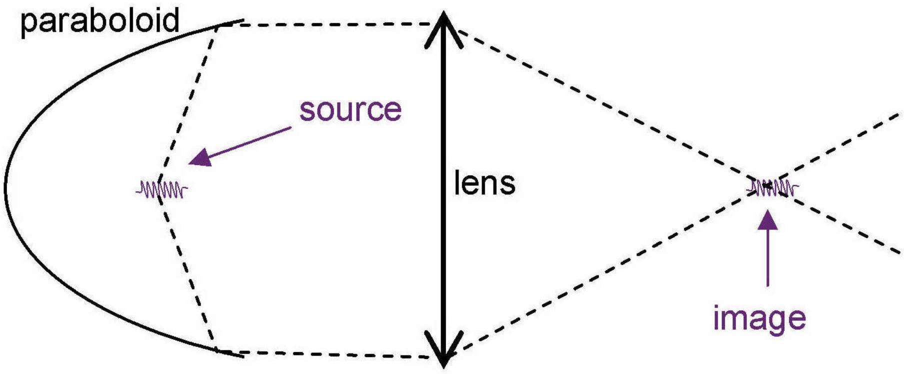
With similar sources, similar condenser NAs, source/condenser étendue as limiting étendue, and similar screen sizes, the average screen irradiance levels are the same for both Abbe and Köhler illumination systems. The choice between the two generally depends upon the type of source available.

Ellipsoidal and Paraboloidal Mirrors

Very efficient collection of light from a source can be achieved using an **ellipsoidal mirror**, placing the source at one of the foci. The source is imaged at the other focus, with light collected over more than a hemisphere.



An alternative is to use a **paraboloidal mirror** to collimate the light from a source and a lens to reimage it. Again, the light from the source is collected over more than a hemisphere.



The forward light is usually ignored in both of these types of designs.

In both cases, the image of the source may not be good quality, but image quality may not be important in illumination systems. Also, obstructions like lamp bases, sockets, and mounting hardware can produce directional anomalies in the radiance of the image.

> If the quality of illumination is important, devices such as lenslet arrays or faceted reflectors may be used.

Spectral Control and Heat Management

Specifications for illumination systems often contain spectral requirements. Some of these requirements can be partially met by the selection of lamp type, but usually some sort of filtering is needed. Also, for visual systems, especially those using tungsten lamps, unwanted heat from infrared light may need to be removed. Again, filtering is needed.

The simplest type of filter is the **absorbing filter** placed in front of the light source. Filter glasses with a wide range of spectral characteristics are available from glass manufacturers. The primary concern with absorbing glass filters is cracking from excessive absorbed heat.

> Often a cracked filter will continue to work just fine.

Interference filters use multilayer thin-film coatings that either transmit or reflect light at specific wavelengths. Cracking is generally not a concern unless the filter is made of an absorbing substrate. These filters are available with a much wider variety of spectral properties than absorbing filters, including narrow bandwidth and sharp cut-off, and can be designed and manufactured to achieve specific custom properties. They are also available for different angles of illumination, typically 0 deg and 45 deg.

> Interference filters shift their spectral properties with incident angle and therefore may not be suitable for uncollimated light with a divergence of more than about 10 deg from the axis.

Hot mirrors and **cold mirrors** are excellent ways to manage heat that must be removed from a light source. A hot mirror reflects infrared light and transmits visible light. A cold mirror reflects visible light and transmits infrared light. The reflector behind the light on a dentist's chair is a cold mirror.

Illumination in Visual Afocal Systems

Afocal visual systems, such as binoculars, take the collimated light from an extended distant object and present collimated light to the eye, but with angular magnification. Therefore, the object appears larger. However, the apparent radiance (and therefore perceived brightness) of the object is the same as that of the naked eye, provided the size of the aperture stop is the same with and without the binoculars. Without the binoculars, the aperture stop is merely the eye pupil. With the binoculars, the aperture stop is the smaller of:

- the pupil of the eye magnified by the angular magnification, or
- the aperture of the objective lens.

In other words, if the collimated ray bundle entering the eye from the binoculars is smaller than the eye pupil, the apparent radiance of the object will be less with the binoculars than with the naked eye. If the pupil of the eye is the limiting aperture both with and without the binoculars, the apparent radiance will be the same.

Binoculars are traditionally designated by two numbers, the first being the angular magnification, the second the diameter of the objective lens in mm. A light-adapted eye pupil with a 2-mm diameter would remain the aperture stop for all of the following common sizes of bird-watching binoculars: 8 × 42, 8 × 32, 10 × 42, 6 × 25, and 10 × 25. These binoculars are generally used during the day. However, marine binoculars, which are used under all lighting conditions, are typically 7 × 50 to accommodate a 7-mm-diameter dark-adapted eye pupil.

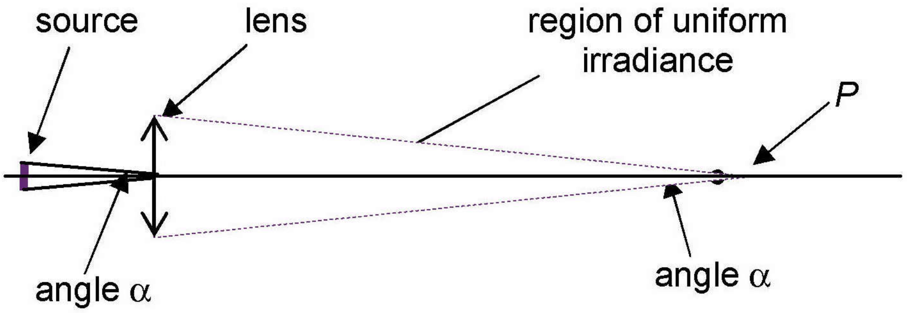
Note that a true point source, such as a star, will have higher apparent intensity (and therefore appear brighter) with binoculars than with the naked eye because more light is collected with the binoculars, but there is no angular magnification.

Searchlight

A **searchlight** can provide uniform irradiance in three dimensions that is extremely insensitive to the position of the irradiated object.

A searchlight consists of a small circular Lambertian source at the focal point of a collimating lens. Anywhere inside the shaded area in the figure below, the source appears as a circular disk at infinity, subtending a full angle α. The entire extent of the source is visible, because it does not completely fill the collimating lens. Since the view of the source is the same anywhere inside this region, the irradiance is the same.

Outside this region and beyond point *P*, the lens restricts the area of the source that is visible. The lens itself appears as a disk of the same radiance as the source. In this region, the irradiance falls off as the square of the distance from the lens.

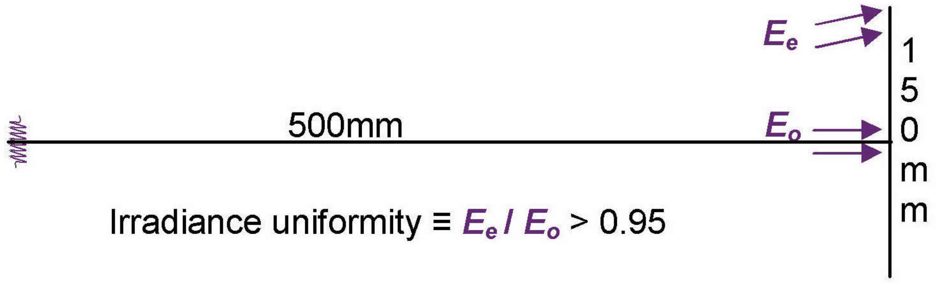


For real searchlights with small sources and large-diameter lenses, the paraxial description above is not exactly valid over the entire shaded region. However, over a relatively small portion of this region, the irradiance is extremely uniform. This region of irradiance uniformity extends not only laterally, but longitudinally as well.

> A searchlight provides a volume of uniform irradiance.

Source at a Distance

A small source at a distance from an object can provide reasonably uniform irradiance across the object. It is somewhat counterintuitive that a bare lamp filament, with its obviously terrible radiance uniformity, can produce excellent irradiance uniformity. For example, a small (assumed Lambertian) lamp filament at 500 mm from a flat object whose largest dimension is 150 mm will provide irradiance uniformity across the object of better than 95% (considering only $\cos^4$ falloff). The same lamp and object at 1.0-meter distance produces nearly 99% irradiance uniformity.

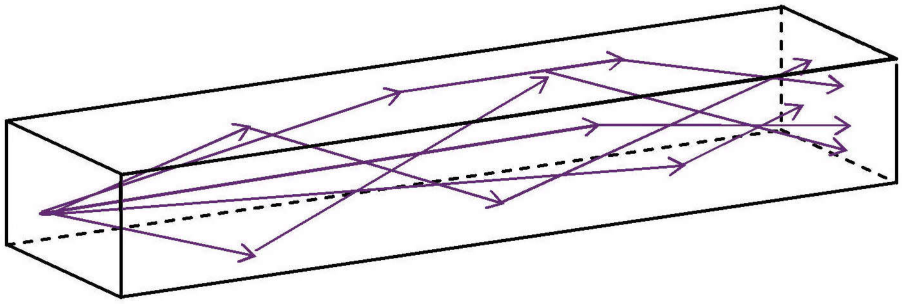


A source of uniform radiance can be created by illuminating a transmission or reflection diffuser with uniform irradiance.

A common calibration laboratory method used to realize a standard of known radiance is to illuminate a reflection diffuser, typically 50 mm in diameter, with a standard of known irradiance, typically a calibrated 1000-W tungsten halogen lamp (ANSI type FEL), at a 500-mm distance. The irradiance uniformity across the diffuser is better than 99.5%. If the reflectance factor of the diffuser is uniform, the radiance uniformity of the standard is also better than 99.5%.

Mixing Rod

A **mixing rod** is a long piece of clear quartz, glass, or plastic. Light entering one face of the rod undergoes multiple total internal reflections emerging from the other parallel face.



Due to the multiple reflections, the **irradiance** at the exit face can be extremely uniform. In a well-designed and illuminated rod, the **radiance** can be quite directionally uniform as well. The directional uniformity of radiance can be enhanced by placing a diffuser at the exit face of the rod or simply frosting the rod-end itself.

Mixing rods can have any shape desired. The rods with plane sides do a better mixing job in most cases.

Typically the rods have an aspect ratio (length to largest transverse dimension) of about 10:1, and are usually about 75- to 150-mm long. They can be clad like an optical fiber, but generally are not. Unlike a fiber, the number of reflections in a mixing rod is quite small, and losses are not a serious problem.

Rather than using a rod with polished faces, it is possible to achieve a similar effect using a mirrored tube with a hollow center.

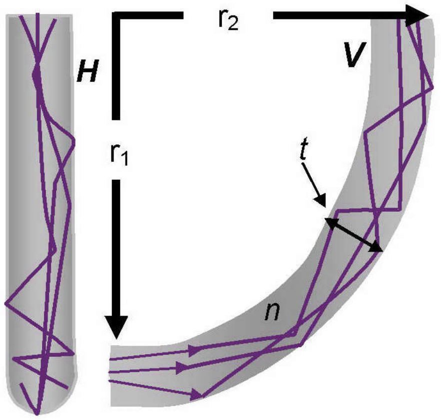
The combination of a rod and its illuminator are sometimes designed by computer simulation. But the degree of uniformity required doesn't always demand this level of complexity, so simple trial-and-error is often sufficient.

Bent Lightpipes

Complex lightpipes made from straight sections, bends, and tapers are common in many industries. **Bent lightpipes** are components used to mix or collect light from different paths that bend around objects or provide light output over an extended region. An example is automotive dashboard illuminators that employ lightpipes coupled to a small incandescent source or an LED. The lightpipe allows the source light to be directed around dials and knobs. The bends allow simple packaging and lower costs at the expense of design complexity.

Any cross-sectional shape, bend angle, bend shape, and so forth is possible, but the simplest is a single, right-angle bend using common-center, circular bends and an arbitrary cross section. A circular cross-section is shown here. Two important slices are called **principal sections**: the vertical (*V*), which shows the bend of the lightpipe, and the horizontal (*H*), which shows the bend going into the page. The vertical slice defines the transmission properties of the lightpipe. For normally incident input light coupled to the lightpipe, there are no propagation losses except Fresnel losses if the **bend ratio**, *R*, is

$$R = r_2/r_1 = 1 + t/r_1 \leq n,$$



where r_1 and r_2 are the two bend radii, t is the lightpipe thickness in the vertical section, and n is the lightpipe index in air. As the input angle increases, there are losses at the limit of this equation, but the equation is transcendental. By decreasing the thickness of the lightpipe, one can increase the acceptance angle such that there is no loss.

More complex parameterization of lightpipes, including uncommon bend centers, noncircular bends, and arbitrary cross sections, can be found in the literature.

Integrating Sphere

Integrating spheres produce illumination that has extremely uniform radiance and irradiance. An integrating sphere is a hollow spherical shell coated on the inside with a highly reflecting diffuse coating. The projected solid angle from any point on a sphere to any element of area on the sphere is the same, regardless of location. This fact combined with the diffuse coating and the multiple reflections cause any light introduced into the sphere to produce uniform irradiance on and radiance of the wall of the sphere. A hole or "port" in the sphere allows this uniform illumination to be used in an optical system.

> The radiance at the exit of an integrating sphere extends to a full hemisphere (π projected steradians). The irradiance at the wall of an integrating sphere is incident from a full hemisphere.

The radiance, L, of the wall of an integrating sphere generated by flux, Φ, introduced into the sphere is

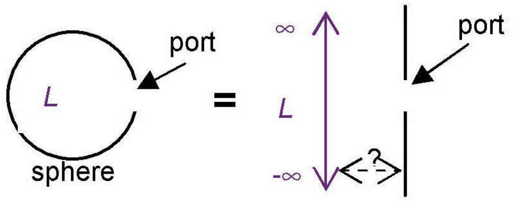
$$L = \frac{\Phi}{\pi \cdot A_s} \cdot M,$$

where A_s is the area of the complete sphere wall, and M is the "sphere multiplier," which is equal to the average numbers of reflections in the sphere. The multiplier, M, is

$$M = \frac{1}{1-\bar{\rho}},$$

where $\bar{\rho}$ is the **average reflectance** of the wall of the sphere, counting the holes as areas of zero reflectance.

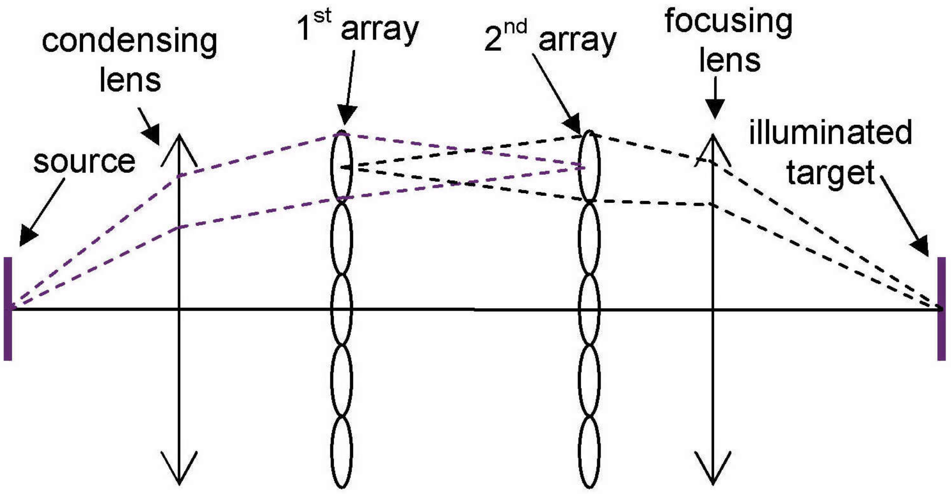
A good working model of an integrating sphere is to consider the port to be a hole in a wall, and, at a totally arbitrary distance behind it, another wall of infinite extent and radiance, L.



Lenslet Arrays

Imaging illumination systems, whether single- or double-lens systems, paraboloidal reflector and lens systems, or single ellipsoidal reflector systems, all suffer from possible nonuniformities in intensity (and consequently also in irradiance). These are due, among other causes, to possible nonuniformities in the source as well as obstructions such as filament support wires, gas discharge electrodes, and LED heat-sink structures.

These nonuniformities can be smoothed out by using a **lenslet array**, an array (usually 2D) of small lenses. Typically, the arrays are used in pairs. In the diagram below, the dotted purple lines show the marginal rays for one of the lenslets in the first array; the black dotted lines show the marginal rays for the corresponding lenslet in the second array.



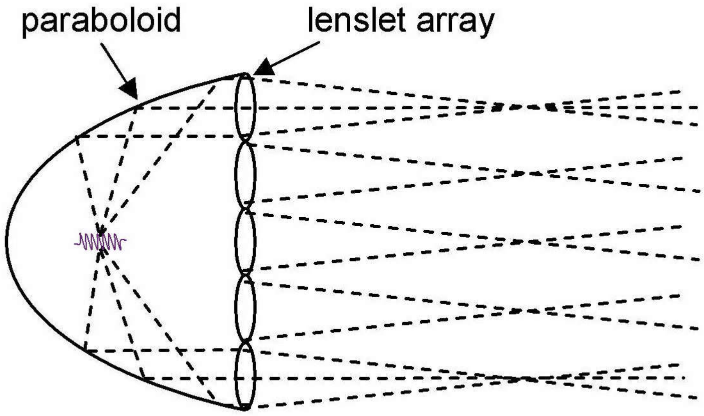
In this configuration, the source is imaged by each lenslet of the first array into the corresponding lenslet of the second array. Each lenslet of the first array is imaged onto the entire target. This overlaying creates uniform illumination of the target. In effect, the lenslet arrays create multiple **Köhler illumination** systems, all superimposed on the target.

> Lenslet arrays are generally designed using illumination design software.

Small Reflectors, Lenslet Arrays, and Facets

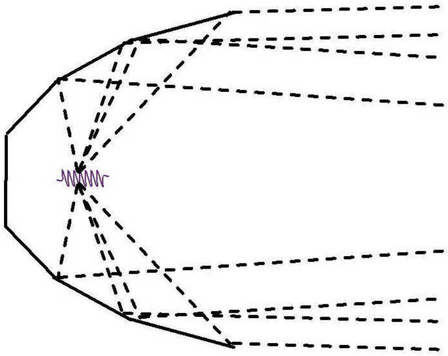
Ellipsoidal and paraboloidal reflectors are often "small" with respect to the lamp dimensions and the distances between the lamp and the reflecting surfaces. In these cases, in addition to the effects of lamp support structures, the size and structure of the lamp itself can produce nonuniformities in illumination.

One method of minimizing these nonuniformities is to include a **lenslet array** in front of the detector. This broadens the beam a little, depending on the *f*# of the lenslets, but it can produce much more uniform illumination than the reflector alone.



Tandem lenslet arrays also can be used to minimize the effects of small reflectors.

Another approach is to break the reflector into small flat **facets**, either radially, circumferentially, or both.



Lenslet arrays and faceted reflectors are usually designed with illumination design software.

Source Modeling Overview

A system software model, whether a simple paraxial design or a detailed design of an illumination system, may fail to agree with experimental results due to the lack of a comprehensive **source model**. For the simplest case, where the optics are far away from the source and collect light over a small solid angle, a point source model or a simple geometrical model of the source may be sufficient. The directional distribution of light from these simple models is usually assumed to be isotropic or Lambertian.

For more efficient designs with optics that are close to the source and collect light over a large solid angle, a more complete model of the source is required to obtain meaningful results. These models must reflect the physical size and shape of the source and should contain directional distributions that account for factors such as filament support wires and lamp envelopes.

Source models are made for all types of sources, including LEDs, incandescent, fluorescent, metal vapor, and high-pressure gas discharge sources. The modeling includes spectral, radiance or luminance distributions, and lifetime aspects. For example, accurate source models for the following have been developed:

- The temperature distribution along an incandescent filament varies from its ends to the center. Additionally, the interior of the filament glows "hotter" due to the re-incident radiation.
- Arc emission sources such as metal halide and HID lamps change their radiance distribution and power output over time due to ablation of the electrodes. These lamps have a deposited material to capture this ablation, called the "salt lake" in continuous sources and the "getter" in a pulsed one.

There are essentially four ways of creating complex source models. Three are described on the next page, while the fourth, not presented here, is based on the physics of emission. This method is outside the confines of this text.

Source Modeling Methods

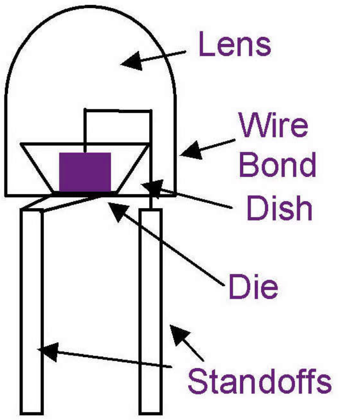
There are three **source modeling methods**, where the accuracy of the model typically increases with number:

1. "Bottom-up" (**geometrical model**): the source geometry starting with the electrodes, supports, and envelope; finishes with the packaging. Emission is assigned to the radiative components.
   - Benefits: No complex measurements; handles re-incident light; provides tolerancing capabilities.
   - Limitations: Emission characteristics assumed; approximate surface and material properties; can include tedious CAD development.
2. "Top-down" (**radiance model**): the optical output of a representative sample of the lamp. These measurements are made with a **goniometer**, which moves a detector around a lamp on two axes. A camera measures the 2D radiance distribution of the lamp from each of many goniometer positions. The resulting 4D model represents a complete description of the lamp that can be used in a computer optical design program.
   - Benefits: Emission is based on physical measurements.
   - Limitations: Does not handle reincident light; is limited by the variance of the number of source samples measured and aligned; and their complex measurement.
3. "Bottom to top" (**system model**): Integrates the bottom-up and top-down approaches to develop a more thorough source model.
   - Benefits: Complete geometrical and radiative models.
   - Limitations: Integration of two submethods.

There are many hybrid methods and methods based on applying the physics of the emission process of a prescribed source. Loosely, the first two methods show agreement to within 25% of experimental results, while the bottom-to-top method shows agreement within 10%. In all cases, rays are assigned, typically in a Monte Carlo approach, to the emission areas.

LED Modeling

The components of an **LED** include the emitting die(s), the lens, the reflecting dish, wire bond and pad, and standoffs. Other components can include phosphors and included detectors.

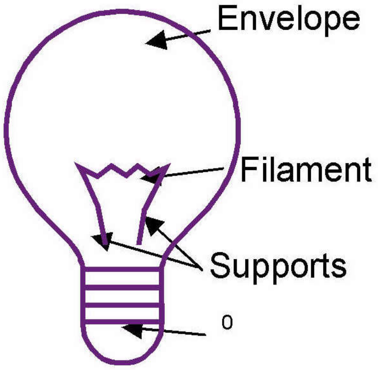


Geometrical modeling is useful to develop LED sources; however, it is difficult to obtain or measure the shapes and sizes of the components within the lens. Radiance modeling suffers because of the large amount of variance between LED samples of one model. The primary issues are the die position within the reflecting dish, the axial position of the die and dish with respect to the lens vertex, and the size and shape of the reflecting dish. Four distinct methods are available for LED modeling:

1. Develop a flat object and assign rays to the surface based upon the intensity distribution provided by the manufacturer. This method ignores spatial variation of the emission.
2. Develop a geometrical model of the LED and assign rays to the emitting surfaces of the die. Optimize the dish shape (typically a cone), size, and the axial offset of the die-dish to the lens vertex. The lens shape must be measured and the die and dish placed at the transverse center of the lens. The model is complete when the intensity pattern from the manufacturer agrees with the ray-trace model.
3. Same as method #2, except develop the layer structure within the die to generate Monte Carlo rays within the active layer(s). This method is tedious for ray tracing due to the index of refraction discontinuity between the die (n = 2.5+) and the epoxy lens (n = 1.45+).
4. Radiance by itself or a system: integrated into #2 or #3.

Incandescent Lamp Modeling

The components of an **incandescent lamp** include the base, filament(s), supports, and the envelope. Other components can include coatings and envelope faceting. Note that the shapes and sizes of components depend on the application. Sources developed for the automotive headlight industry provide the highest level of tolerance from one sample to another.

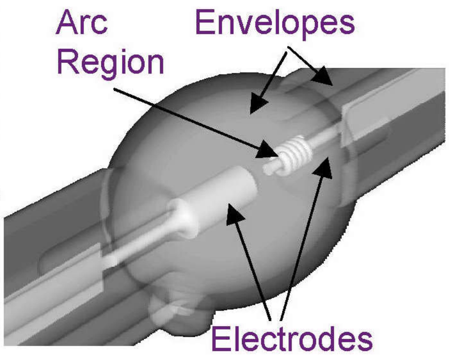


Both geometrical and radiance methods are useful for incandescent source modeling. Radiance modeling is better suited to this source since a goniometer can be focused on the filament source, while the glass envelope supplies little effect on overall optical ray paths. Only light rays that are re-incident (approaching grazing incidence) on the envelope show adverse effects. Geometric modeling involves breaking the glass envelope to gain access to the internal components. This process requires the use of calipers to measure the coil spacing, the thicknesses and lengths of the components, and the number of coils. Provided parameters can help with this process:

- **Maximum overall length (MOL):** Overall distance that includes the base and pins.
- **Light center length (LCL):** Distance between the center of the emitter and a defined reference plane.
- **Filament type:** Designated by @-#, where @ is a series of letters (e.g., C = coiled, CC = coiled coil, and SR = straight ribbon), and # is a number providing an arbitrary pattern for the filament supports.
- **Bulb type:** Designated by @-#, where @ is the bulb shape (e.g., T = tubular), and # is the diameter in eighths of an inch.
- **Base type:** Innumerable types that have no shorthand notation to describe them. Examples include screw, mogul, bipin, and prong.

Arc and Fluorescent Lamp Modeling

The components of an **arc lamp** include the base(s), electrodes, and envelope(s). Other components can include coatings, salt lake (continuous) or getter (pulsed), and ignition wire (flashlamp). The optical radiation is represented by a virtual object called the arc. Note that the aspects of components depend on the application. Automotive headlight arcs provide the highest level of accuracy from one sample to another.



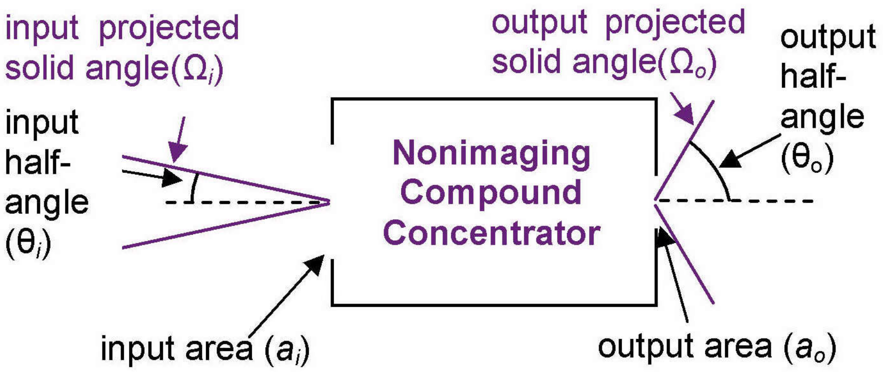
Radiance modeling is especially suited to this source since geometrical modeling cannot effectively represent the arc. The arc must be approximated with a cylinder, tube, or some other geometric shape. Radiance modeling is also suited to this source because a goniometer can be focused on the arc. Due to the typical smaller sizes of these sources compared to incandescent sources, the effect of re-incident rays is more pronounced. Thus, methods to integrate a simplified measurement of the radiance distribution into the geometrical model have been employed. One such method uses the **Abel transform** based on a single image capture of the arc. The Abel transform assumes symmetry of the arc shape and revolves it around a localized centroid of the arc source. Such system models are the most effective way to model such sources.

Fluorescent lamps include the tube and base(s). These are the simplest sources to model other than the complex geometry of compact fluorescent lamps now available. After the geometry is entered, the inner surface of the tube acts as the emitter. Internally, mercury vapor is excited, releasing UV radiation, which is then converted into visible light upon being incident on the phosphor. Geometrical modeling is better suited to this source due to the large size and simplicity of the configurations.

CX-0693

Nonimaging Compound Concentrators

Nonimaging compound concentrators were first developed for solar energy collection to concentrate the **irradiance** from the sun. In solar collection, depending on the degree of sophistication of the sun tracking system, the range of sun input angles can be fairly small. The collectors (solar cells, water pipes, etc.) respond essentially to irradiance and can be illuminated at any angle. The compound concentrator trades off between area and solid angle, presenting a large collection area to the sun (collecting over a narrow solid angle) and delivering the energy to a smaller area (and over a wider solid angle). These devices come close to achieving the theoretical maximum concentration (in three dimensions).



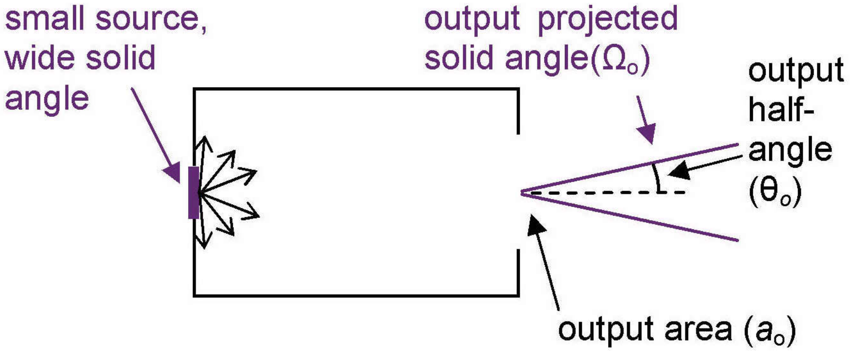
If the output projected **solid angle** is the maximum, π, ($\theta_o = 90$ deg), the concentration is maximum:

$$\frac{a_i}{a_o}(\max) = \frac{1}{\sin^2 \theta_i}.$$

Nonimaging compound concentrators are designed using the **edge-ray principle**, which directs all rays that are at the maximum input angle (θ_i for $\theta_o = 90$ deg in the drawing above) to the edge of the output aperture. All rays at input angles less than this maximum are directed inside the output aperture with no concern for image quality. Often this angle, θ_i, is called the **acceptance angle**, θ_a.

Concentrators as Luminaires

Nonimaging compound concentrators are used in illumination as **luminaires**—devices used to direct the light from a source for illumination. For illumination, they are used in the reverse direction from their configuration in solar collection; they collect light from as large an angle as possible from a small source and direct it over a smaller angle through a larger aperture. For solar collection, they collect energy over a large area and a small angle, delivering it to a small area.



Nonimaging compound concentrators are efficient because:

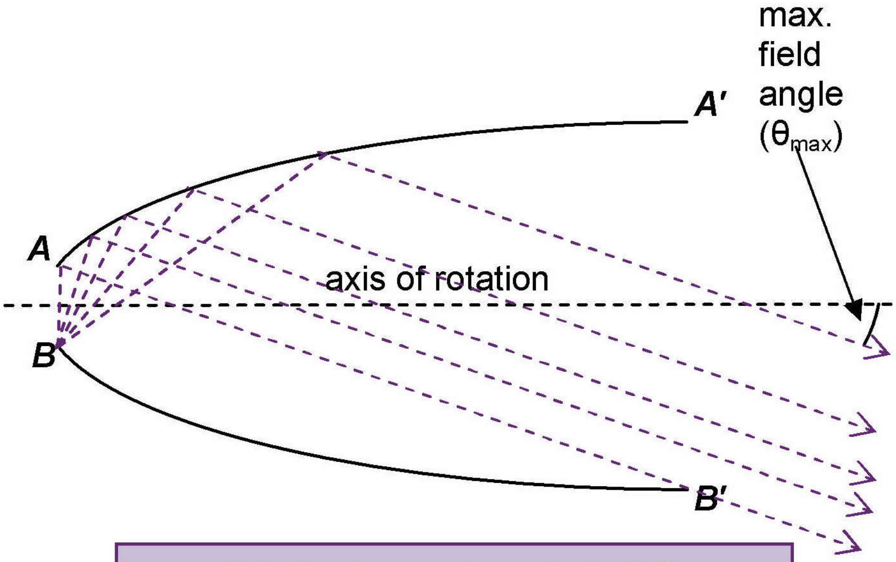
- They collect light from the source over a very large solid angle.
- They are designed using the **edge-ray principle**, keeping all the energy within the intended field.

> Imaging systems are designed to be best on axis, with the edges of the field "spilling over." Nonimaging compound concentrators are designed to be best at the edges of the field, keeping all the energy inside the design boundaries.

Nonimaging concentrators used as luminaires are usually composed of an internal mirror surface with the figure of a **compound parabolic concentrator (CPC)**, **compound elliptical concentrator (CEC)**, or **compound hyperbolic concentrator (CHC)**. Dielectric filled concentrators that employ total internal reflection are also used.

Compound Parabolic Concentrators

The **compound parabolic concentrator (CPC)** is a common shape of nonimaging concentrator used for illumination. A CPC is formed by a parabola with its focus at one edge of the entrance (small) aperture, rotated around an axis that is perpendicular to and through the center of both apertures. CPCs can be quite long.



B is the focus of parabola *AA*′.
A is the focus of parabola *BB*′.

The complete equation for the surface of a CPC can be found in the equation summary in the Appendix.

The ratio of the diameter of the small and large apertures is determined by maximum field angle

$$\frac{d_o}{d_i} = \frac{1}{\sin\theta_{max}},$$

where d_o and d_i are the diameters of the output (large) and input (small) apertures, respectively.

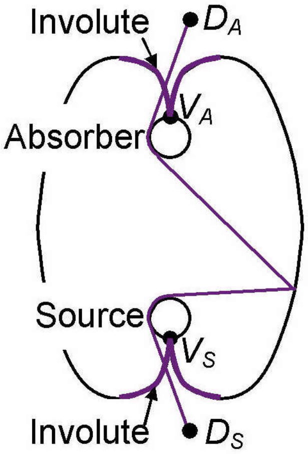
The length of the concentrator is

$$\text{Length} = \frac{d_o + d_i}{2\tan\theta_{max}}.$$

Compound Elliptical and Hyperbolic Concentrators

The **compound elliptical concentrator (CEC)** and **compound hyperbolic concentrator (CHC)** work in the domains of finite and diverging conjugates, while the CPC worked at infinite conjugates. For CECs, the CPC-development methods can be used. To visualize their shapes, consider what is called the **string method**, where the string acts as the edge ray:

- Choose two points, D_A and D_S.
- Select a length of string that allows the pen, P, to read points V_A and V_S.
- While pulling the string taut with P, sweep out the shape on one side of the reflector.
- Flip the string to the other side and repeat.



For a CPC, the absorber points D_A and V_A are located at infinity such that a constant angle, θ_a, is obtained. This method is adaptable to handle nonplanar sources. If the source, as shown in the figure, impedes on the string path, then a secondary region called the **involute** is formed. The involute ensures that rays with output angles less than θ_a are transferred by the reflector. Such reflectors with nonplanar sources or absorbers are better denoted as edge-ray reflectors. Note that the terms "absorber" and "source" are swapped for collector design.

The CHC is designed with the **flow-line method**, which treats light rays as fluid flow. Due to the conservation of étendue, we find vectors that define the geometrical flux through the amplitude and their directions define the flow line. The flow lines are hyperbolae. A reflector can be placed along one of the rotationally symmetric flow lines, and due to invariance there is no adverse effect on light emission from a Lambertian source located at the flow line origin.

Tailored-Edge-Ray Design

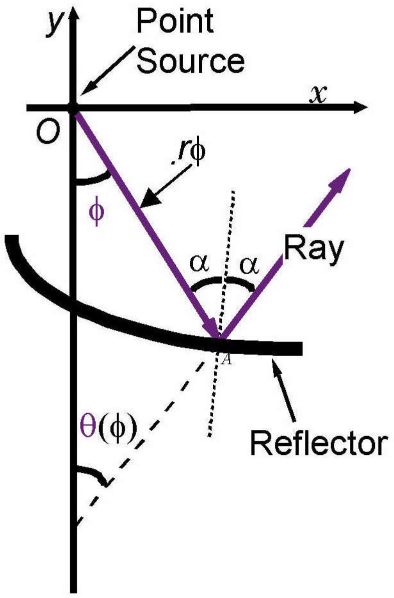
The involute sections of edge-ray luminaires for nonplanar sources or absorbers indicate that the acceptance angle does not need to be constant over the extent of the reflector. Designs with a functional acceptance angle are called **tailored-edge-ray reflectors**. Using the figure, the equation that governs their shape for a point source design is

$$r(\phi) = r_1 \exp\left[\int_{\phi_1}^{\phi} \tan\left(\frac{s-\theta(s)}{2}\right) ds\right],$$

where r is the distance from the point source to the reflector, r_1 is the distance for the polar angle ϕ_1, and θ is the desired output intensity from the reflector. θ is the variable acceptance angle (note that "acceptance" is a holdover from solar concentrator design). For uniformity at the target,

$$\theta(\phi) = \arctan\left[\tan\theta_1 + \int_{\phi_1}^{\phi} I_{\text{src}}(v)\,dv\right],$$

where I_{src} is the intensity distribution emitted by the point source.

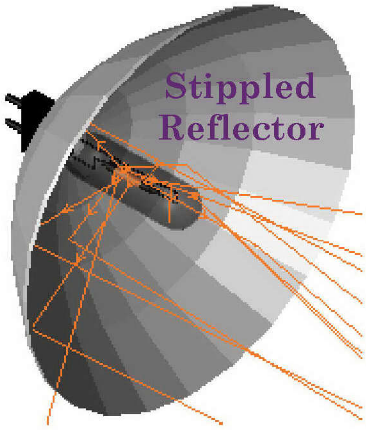


To allow for finite-extent sources, the first equation can be modified, and the reader is encouraged to consult the literature.

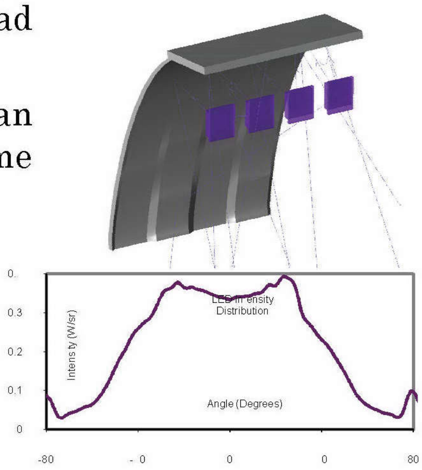
Though the formalism presented here might appear daunting, tailored-edge-ray design is a powerful tool to design optimal optics around both the emission aspects of the source and the desired irradiance distribution at the target. The one caveat is that tolerances are quite demanding unless one places sufficient leeway into the source intensity distribution (I_{src}).

Faceted Reflector Design

Essentially there are two design procedures for **faceted reflectors**: those based on the **tailored-edge-ray** method and those that provide a **stippled illumination pattern**. Stippling means that the target irradiance distribution is created from the overlap of the light from different segments of the reflector. This washes out any structure that could be imaged from the sources, such as a filament and its supports. Thus, the designer builds a basic reflector shape, such as parabolic, and then replaces the one smooth reflector with a series of flat, areal segments. This type of faceted reflector can be found in LCD and overhead projectors.



Tailored-edge-ray reflectors can also use this effect with some added benefits:



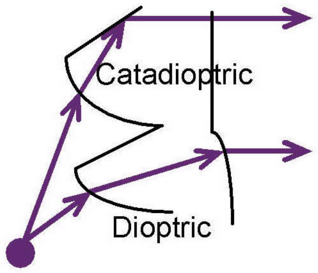
- Energy conservation restrictions mean the reflectors grow large, but faceting allows the shape to be "restarted" to minimize the overall volume.
- Facets can individually address different por-tions of the desired target distribution.
- Tolerancing is improved since various allowances can be incorporated as a function of segment position.

These reflectors are typical in the automotive headlight industry and are increasingly used in other applications. This example (LED) shows the utility of faceting. The LEDs' intensity distribution pattern, along with uniformity at the target, gives the reflector shape shown here.

Advanced Nonimaging Optic Design

There are a number of advanced nonimaging design algorithms, such as **nonimaging Fresnel lens design**, **nonedge-ray design**, and **simultaneous multiple surfaces method (SMS)**. Nonimaging Fresnel lens design is used in lighthouses, solar concentrators, traffic lights, and automotive lamps. The in-expensive, small-volume optics are thin dielectrics, plastic or glass, with two types of Fresnel elements:

- **Catadioptric:** uses two refractions and one TIR to bend the light in the desired direction.
- **Dioptric:** uses two refractions to bend the light in the desired direction.



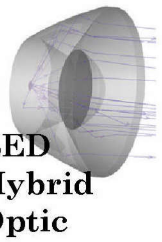
Dioptrics are used toward the lens center while catadioptrics are used once Fresnel losses become large. The TIR condition reduces the angles of incidence on the two refractive surfaces.

Nonedge-ray design follows the equations of tailored-edge ray design but adds two additional factors:

- System performance criteria drive optimization; and
- Multiple extended-size sources are allowed.

This design method trades between system performance and transfer efficiency from the source to the absorber. It is used in multiple small-source applications, such as LED lighting and diode-laser pumping.

SMS provides for multiple ray paths from the source to points on the to-be-generated optical surfaces of the device. Refraction, reflection, and TIR are used in conjunction to generate the multiple surfaces and provide the optimal output angular spread from the optic. SMS is part of a family of optics called **hybrid optics** that use many different optical phenomena for their operation. A primary example is the pseudo-collimating lenses used for high-brightness LEDs.



LED Hybrid Optic

Displays—Overview

A multitude of existing **displays** incorporate different illumination strategies to provide a lit screen. Optical display technologies include **backlighting**, **projection**, and **organic LED (OLED)**.

Backlit displays use large liquid crystal (LC) modules that are lit from the rear by small sources coupled to a TIR element that spans the extent of the screen. The TIR is frustrated by structures placed on a surface of this element. Sources used in backlit displays include **cold-cathode fluorescent lamps (CCFL)** and LEDs, in which the ejected light proceeds through many additional layers, including polarizers, the LC, and diffusers. Additional layers may include a **brightness enhancement film (BEF)**, which recirculates ejected light until it is in the desired angular range. The next few pages describe the components of a backlit display in more detail.

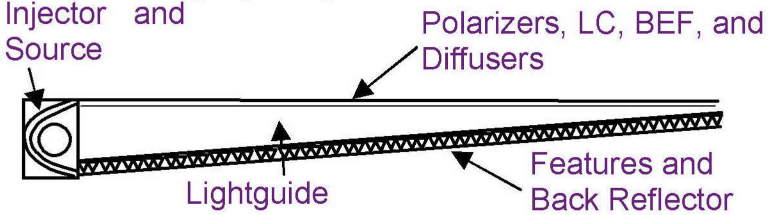
Projection displays use smaller **SLMs** in different spectral ranges to multiplex a full-color image. The illumination components include a broadband source (e.g., a narrow-gap arc lamp or LED), a reflector to capture the emitted radiation, lenslet arrays (often called fly's eyes), and dichroic filters to separate the light into the desired spectral ranges (typically red, green, and blue). There are both **front-projection displays** and **rear-projection displays**. Front-projection displays use distinct spectral channels to illuminate the screen; however, this increases cost and can reduce tolerances. Rear-projection displays fold the system in order to maintain a smaller display depth. Projection displays are discussed in more detail later.

Unlike backlit and projection displays, **OLED displays** deposit pixel emitters onto a substrate. These emitters provide both the illumination and display information, so the design demands for the illumination engineer are negligible. OLED modules can be used in projection displays.

Backlit Display Components

Standard components of a **backlit LCD** include:

- **Source:** Typically CCFL, LED, or **electroluminescent (EL)**.
- **Injector:** A specular or diffuse reflector that captures and injects the light into the lightguide.
- **Lightguide:** A dielectric, typically acrylic, that captures the injected light via TIR. Features are placed on the backside of the lightguide to break the TIR condition. The lightguide is also wedged using decreasing thickness with increasing distance from the injector.
- **Features:** Paint patterns or geometric structures to frustrate the TIR. The density and/or depth of the features increases with distance from the injector to provide uniform illumination over the screen. The geometric structures can be holes (extending into the lightguide) or bumps (extending out of the lightguide).
- **Back reflector:** A diffuse or specular reflector placed below the features to capture and recirculate any light that is emitted from the lightguide backside.
- **Polarizers:** Two crossed linear polarizers placed on the display output side with an LC placed in between.
- **Liquid crystal:** Sandwiched between the two crossed linear polarizers to rotate the polarization by 90 deg for a pixel that has information content. Closely placed pixels provide for the color content (e.g., three pixels to provide red, green, and blue).
- **Diffusers:** Sometimes placed on the output side of the lightguide to provide better angular uniformity from the display.
- **Brightness enhancement film:** A microstructure, such as a prism, to select a desired angular output range while the higher angular content is recirculated to increase display brightness.



Backlit Display: Source and Injector

Small sources are preferable for backlights to reduce the overall display volume. The source can be located to the side of a lightguide or placed directly behind the polarizers and LC. The former allows for thin displays at the expense of lightguide complexity; the latter increases the depth due to the removal of the lightguide, and careful design is required to provide uniform luminance. Three standard sources are used: **CCFLs**, **LEDs**, or **EL** films. CCFLs are small-diameter lamps that run the length of one or more sides of the display. For LED backlights, multiple LEDs are used to provide the required luminance level. They can be white-light emitters, a combination of multiple colors (e.g., red, green, and blue), or a combination of color-emitting LEDs and white-light emitters. EL films provide single-color background displays with information shown in black. Examples include watch faces and automotive dashboards. They work by passing current through the EL material, which then emits spatially uniform Lambertian light. EL backlights have no need for a lightguide because the EL is mated to the back of the LC-polarizer module.

An **injector** is standard for any type of backlighting scheme. For a backlight whose source is located to the side of a lightguide, either diffuse or specular reflectors are placed around the source to better capture the emitted radiation. Standard shapes for a CCFL include spherical, parabolic, and elliptical troughs. For LEDs, dielectric (especially acrylic) couplers akin to the hybrid optics presented are used. The output aperture of the injector is mated to the input aperture of the lightguide. For backlighting without a lightguide, reflectors are often placed around the sources to assist in directing the light and to provide uniform luminance from the display. The simplest case is the **lightbox**, which is a highly reflecting, diffuse material placed around the sources over the extent of the screen backside. Lightboxes are analogous to integrating spheres.

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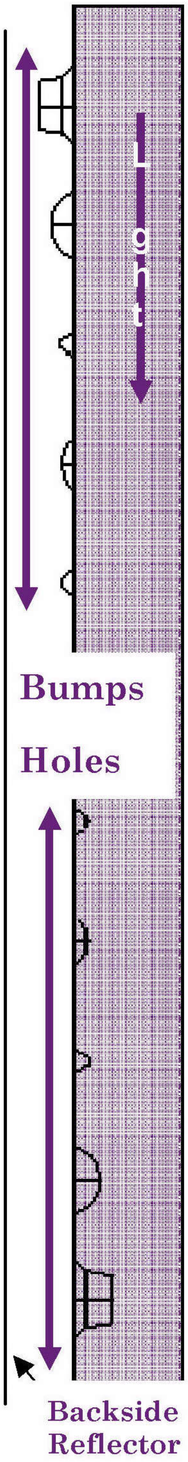
Backlit Display: Lightguides, Features, Reflectors

Plastics are best suited for **backlight lightguides** because they can take advantage of **injection molding**. The thickness at the injector end of the lightguide depends on the screen size, with larger displays requiring thicker lightguides. The lightguide is thinned with increasing distance from the injector. This thinning assists with ejection of the trapped TIR light, because as the lightguide cross-sectional area decreases, the conservation of étendue demands an increase in the angular extent.

Structure or **features** are added to the backside of the lightguide, i.e., on the wedged surfaceside because the backside has more distance for the light to spread over the spatial extent of the display. Initially, paint patterns were used to cause the ejection; however, the paint must undergo a separate and costly process, and the paint spots provide little direct control of the resulting angular distribution. For this reason, replicated geometrical structures are added during injection molding either as **holes**, which extend into the lightguide, or **bumps**, which extend out of the lightguide. Geometrical shapes, as shown in the figure, include hip roofs, spheres, and ellipsoids. The density and/or depth of these features increases with distance from the injector. The design of such feature patterns is from the **diffusion equation**, followed by optimization for improved performance.

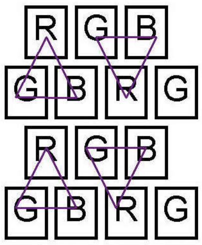


Light leaked through the back feature-side of the lightguide is caught with a reflector, diffuse, or specular, which is placed below the lightguide. The **backside reflector** provides recirculation and better efficiency.

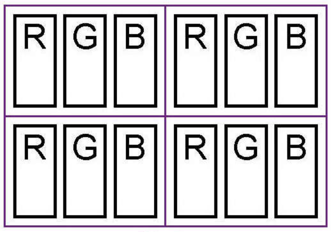
Backlit Display: Polarizers, LC, and BEF

There are a number of additional components that comprise an LCD, including two **linear polarizers** and the **twisted-nematic LC module**. The first polarizer passes linear polarization at one orientation, while the second passes linear polarization orthogonal to the first. The LC is sandwiched in between these two polarizers, and in a pixel's transmissive state, it rotates the light that exits the first polarizer by 90 deg. A pixel in a nontransmissive state absorbs the incident radiation. The LC module also has glass substrates on both sides of the LC, and on each glass substrate there are transmissive **indium-tin oxide (ITO)** electrodes. A **spectral filter mask** is inserted to provide color output from the display. Typically, a three-color mask is used, where neighboring subpixels pass red, green, or blue. The combination of these pixels forms a display through resolution considerations of the viewer. There are a number of **color-pixel patterns** including:

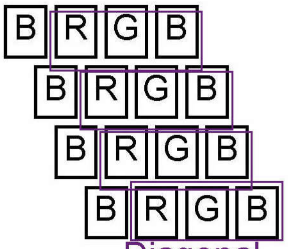
- **Triangular** or **delta:** better for motion pictures;
- **Stripes:** better for television; and
- **Diagonal:** better for motion pictures.



Triangular

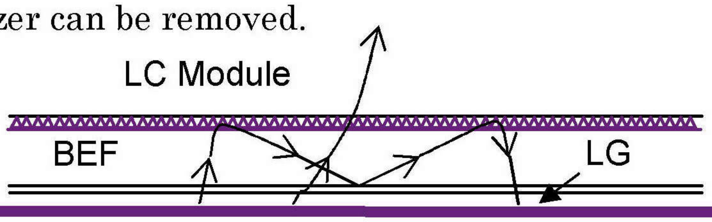


Stripe



Diagonal

A **BEF**, a replicated structure of microprisms, recirculates emitted light until it is in the desired angular range. The BEF is situated just below the polarizers and LC. A **dual brightness enhancement film (DBEF)** incorporates the polarization into the optic such that the first linear polarizer can be removed.



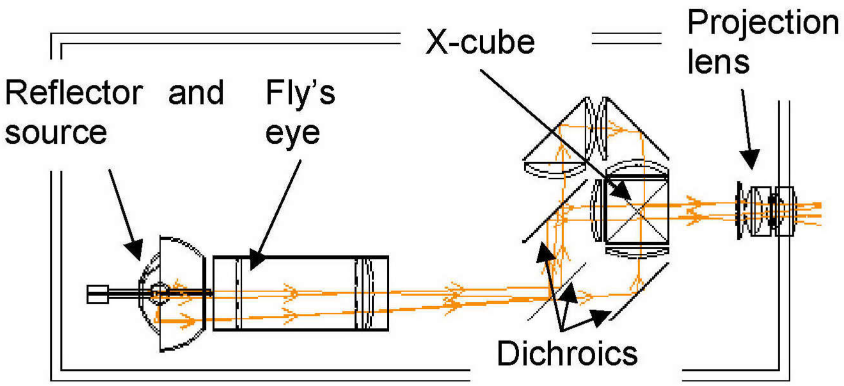
Projection Displays

Projection displays typically use three channels— red, green, and blue—to develop the object to be displayed by the projection lens. Each of the channels uses a **spatial light modulator (SLM)** to generate this object. One-channel systems use color filter wheels to temporally generate the scene. There are essentially three options for the SLM:

- Transmissive LCs akin to those used in backlighting;
- **Digital light processing (DLP)** modules, which incorporate millions of micromirrors over their surface area; or
- Reflective LCs, such as **liquid crystal on silicon, (LCoS)**, which integrate the LC with the circuitry.

The SLMs are microdisplays that use magnification from the projection lens to generate the screen image. An X-cube combines the three spectral channels, and the resulting "object" is projected onto the screen.

The illumination components of a projection display include the source, a reflector, and fly's eye lenses and/or straight lightpipes. The source is typically a narrow-gap arc or even LEDs. The reflector (conic, edge-ray, or faceted) is specular, and it captures most of the source emission. The fly's eye provides better spatial uniformity over the SLMs by creating several images of the source. The lightpipe mixes the light to provide better spatial uniformity. The overall illumination system is typically arranged in a Köhler scheme to hide the source structure.



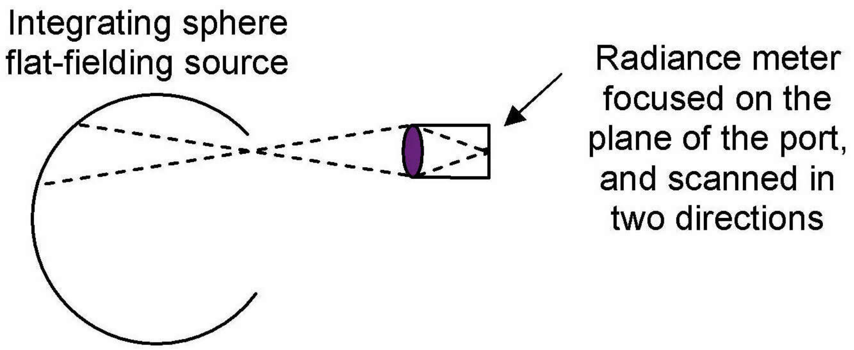
Mapping Flat-Fielding Sources

High-performance camera systems such as airborne and satellite cameras generally go through a process known as **flat-fielding**. The camera is presented with a large-sized extended light source that has nearly perfectly uniform radiance. Since the flat-field source is uniform, any pixel-to-pixel nonuniformities in the camera are inherent to the camera and can be remedied with image processing.

Generally, flat-fielding sources are realized by internally illuminated integrating spheres. Spheres with exit ports of about a 50-cm diameter are common. Ports of over a meter in diameter are sometimes needed depending on the aperture of a single large camera or the combined apertures of an array of smaller cameras. Radiance uniformities of 98% or 99% or better are the norm.

To verify that the flat-fielding sources have been designed properly and that there are no deficiencies in their manufacture, they are mapped for radiance uniformity. The mapping is done with a radiance meter, which is often photopically filtered for no other reason than commercial availability and the desire to band-limit the silicon detector to a region of good sensitivity.

The radiance meter is operated either in a collimated mode or is focused on a small spot in the plane of the exit port. Keeping the viewing direction constant, the meter is scanned in two directions to create a radiance map of the source.



Goniophotometers

Light sources designed to produce useable irradiance (automobile headlamps, roadway luminaires, and interior lighting fixtures) as well as those designed to produce useable intensity (automobile tail lights, traffic signals, aircraft and marine running lights) are all characterized by **goniophotometers**—devices used to measure the directional distribution of light from sources.

A goniophotometer consists of a small detector placed at a distance from the source where **intensity** is meaningful, (i.e., the inverse-square law applies). Except for highly collimated sources such as searchlights, a distance from the source of five to ten times the largest dimension of the source is usually sufficient. The lamp or detector (or a combination of the two) is moved to map the intensity distribution of the source.

Goniophotometers are classified as type A, B, or C depending on how they are constructed. This can be confusing because, in addition to three types of physical construction, there are three variations of spherical coordinates for reporting data that are also called types A, B, and C. These usually, but not always, match the type of goniophotometer used. Details of the three coordinate systems are shown on the next page.

Types A and B goniophotometers are similar in that the luminaire is mounted on a device with horizontal and vertical axes and a distant fixed detector.

Type C goniophotometers move the detector around the luminaire on a horizontal axis and rotate the luminaire on a vertical axis. Sometimes, for large luminaires, involving large distances, the detector is fixed and a large high-quality mirror moves on a horizontal axis, directing the light to the detector.

Type C goniophotometers are necessary for measuring lamps that are sensitive to the burning position.

Types A, B, C Goniometer Coordinate Systems

All are spherical coordinate systems.

Type A spherical coordinates:
Polar axis: vertical
Label on vertical angles: *Y*
Label on horizontal angles: *X*
Range of Y: –90 (nadir) to +90 (zenith)
Range of X: –180 (left, from luminaire) to +180
Straight ahead: $Y = 0$, $X = 0$
Primary uses: optical systems, automotive lighting

Type B spherical coordinates:
Polar axis: horizontal
Label on vertical angles: *V*
Label on horizontal angles: *H*
Range of *V*: –180 to +180
Range of *X*: –90 (left, from luminaire) to +90
Straight ahead: $V = 0$, $H = 0$
Primary uses: floodlights

Type C spherical coordinates:
Polar axis: vertical
Label on vertical angles: *V*
Label on horizontal angles: *L* (lateral)
Range of *V*: 0 (nadir) to 180 (zenith)
Range of *L*: 0 (along primary axis of luminaire) to 360
Straight down: $Y = 0$, $X = 0$
Primary uses: indoor lighting, roadway lighting

"Snapshot" Goniophotometers

Conventional **goniophotometers** take a long time to produce an **intensity** mapping. In addition, they must have precise motion control to achieve the desired angular resolution. As such, they are well suited for characterizing luminaire designs, but not really useful for quality control or sorting of LEDs, for example. For these applications, several versions of rapid "snapshot" goniophotometers have been developed:

- Rapid-scan goniophotometers
- Multiple-detector goniophotometers
- Tapered fiber bundle goniophotometers
- Camera-based goniophotometers

Rapid-scan goniophotometers are small devices used to characterize LEDs and the output of optical fibers. They operate on similar principles to the conventional type C goniophotometers, but motions are much faster, making measurements in seconds rather than minutes.

Multiple-detector goniophotometers place numerous discrete detectors in the intensity field of interest and capture the entire intensity distribution at one time. The angular resolution is restricted to the spacing of the detectors.

A tapered fiber optic bundle can be manufactured with one concave spherical face with all the fibers directed toward the source. At the other end of the bundle, the fibers can be aligned with the pixels of a detector array. The detector array captures the entire intensity distribution at one time.

Camera-based goniophotometers place a diffuse reflecting surface (flat or concave) at an appropriate distance from the source, and view the light reflected from the surface with an imaging photometer that, together with the reflecting surface, is calibrated to capture the entire intensity distribution in one "snapshot."