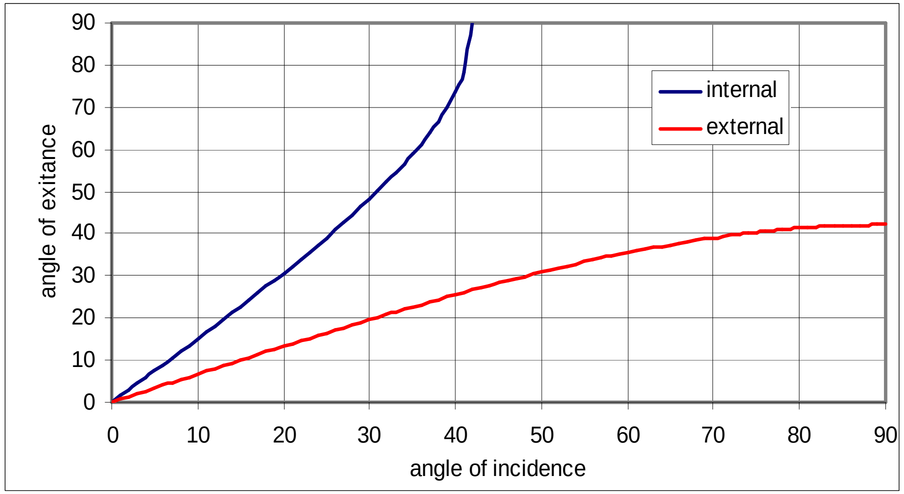
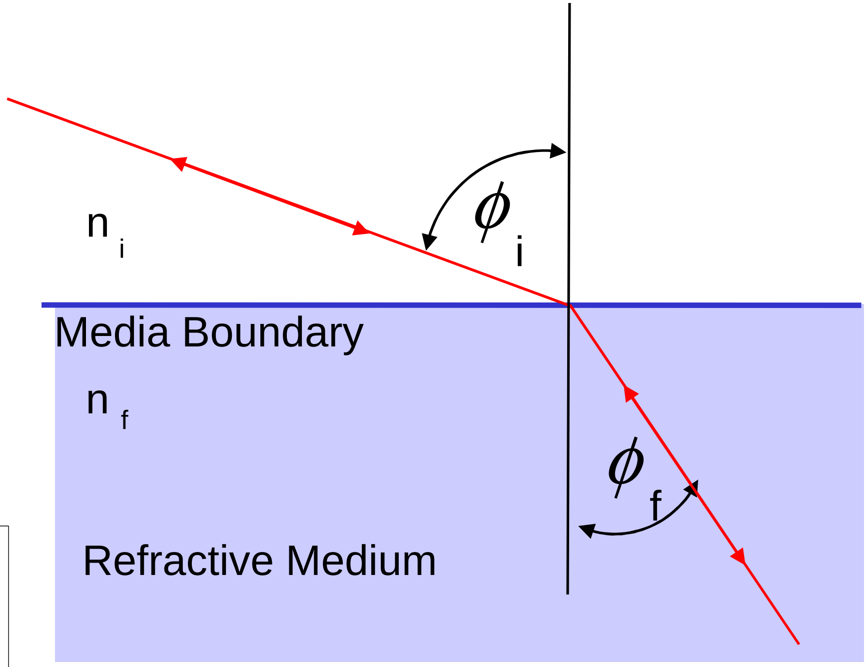
Basic Optical Concepts

Refraction- Snell's Law

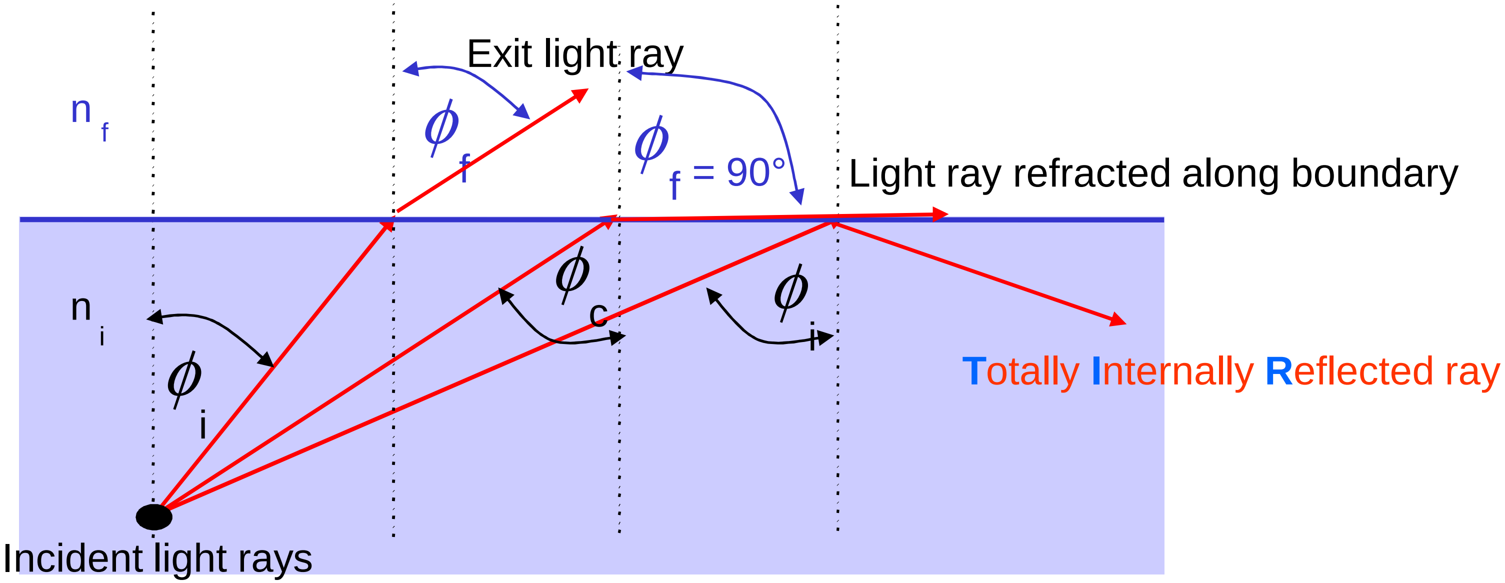
Snell's Law:

$$\frac{Sin(\phi_i)}{Sin(\phi_f)} = \frac{n_f}{n_i}$$





Refraction and TIR



Critical angle for total internal reflection (TIR):

ϕ_c= Arcsin(1/n) = 42°

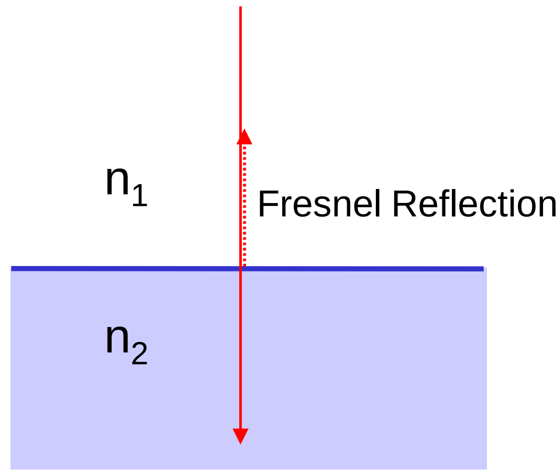
(For index of refraction n_i =1.5,n= 1 (Air))

„Total internal reflection is the only 100% efficient reflection in nature"

Fresnel and Reflection Losses

Reflection:

-TIR is the most efficient reflection:
An optically smooth interface has 100% reflectivity
-Metallization: Al (typical): 85%, Ag (typical): 90%

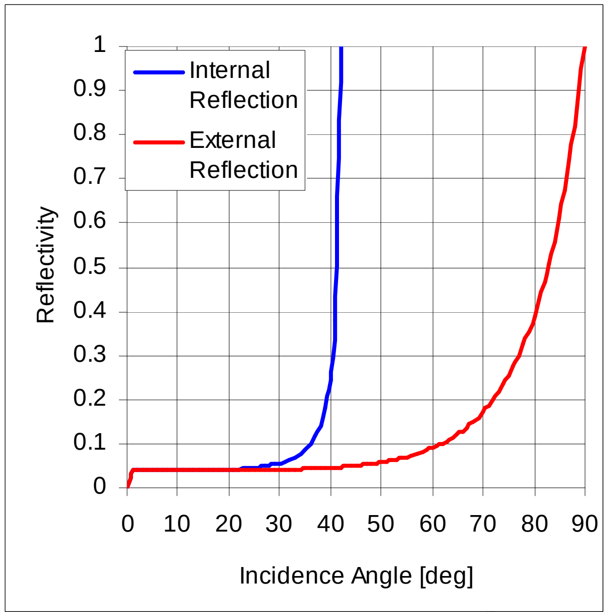


Refraction:

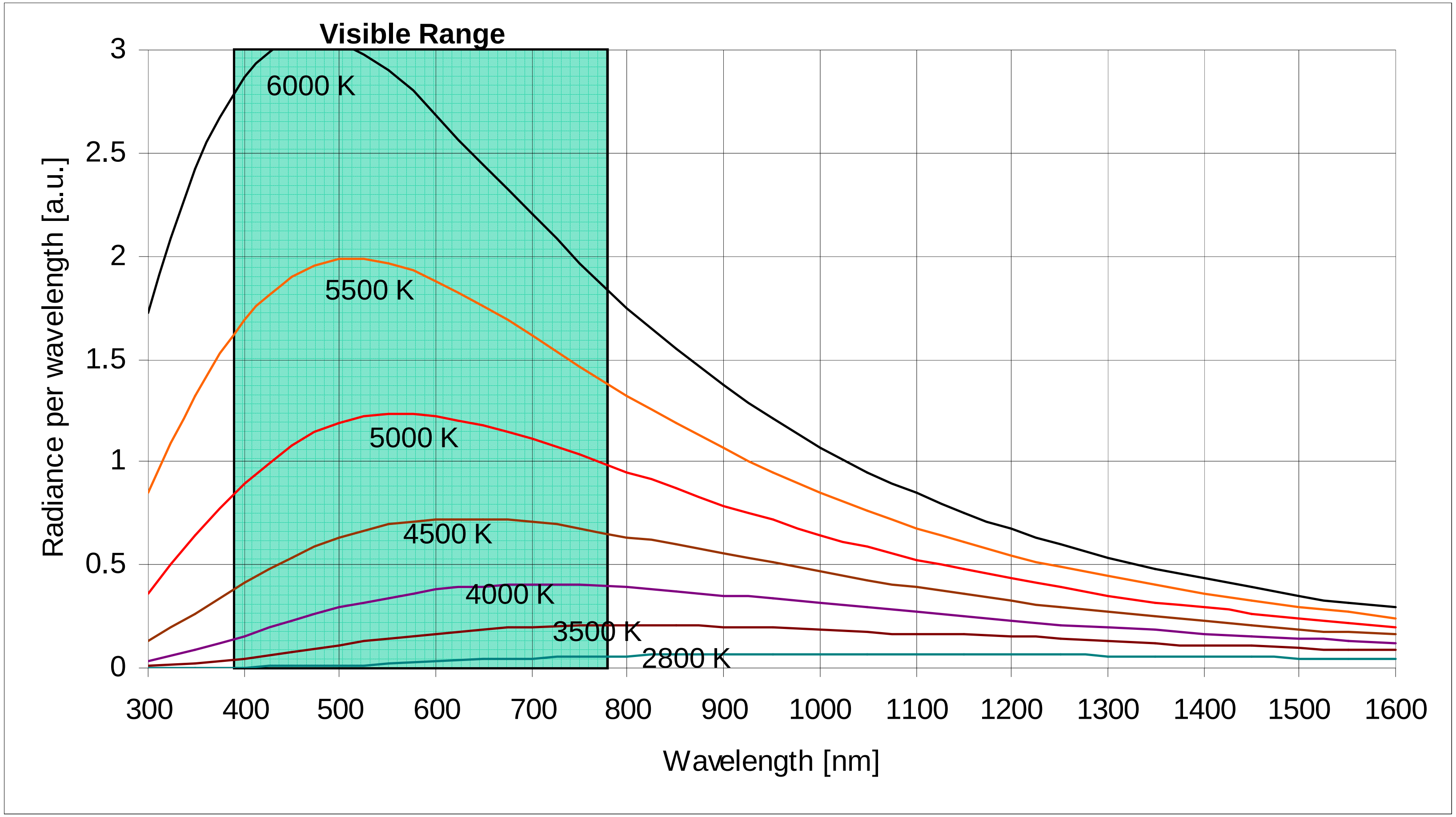
-There are light losses at every optical interface
-For perpendicular incidence:

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2} \right)^2$$

-For n_1 =1 (air) and n_2=1.5 (glass): R=(0.5/2.5)^2=4%
-Transmission: T=1-R.
-For multiple interfaces: $T_{tot} = T_1 * T_2 * T_3 \ldots$
-For a flat window: T=0.96^2=0.92
-For higher angles the reflection losses are higher

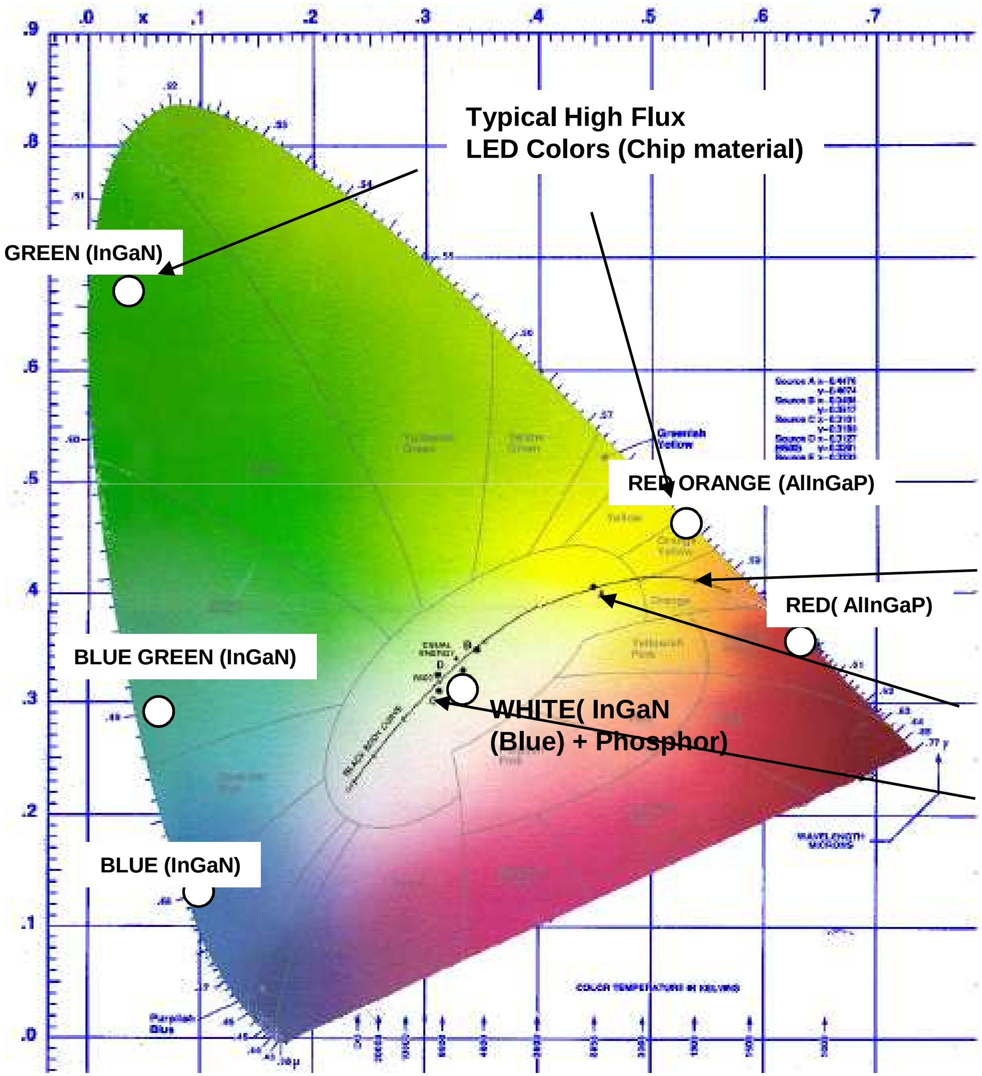


Black body radiation & Visible Range



- Every hot surface emits radiation
- An ideal hot surface behaves like a “black body”
- Filaments (incandescent) behave like this.
- The sun behaves like a black body

CIE 1931 Color Palette



CIE 1931 Color Diagram:

-Colors are represented by (x,y) coordinates
-Different source spectra can have the same (x,y) point, same color appearance
-Two light sources represented as two points in diagram can mix (by varying their intensities) to any color on a straight line between them
-Pure Colors (spectrum has only on wavelength) are on “rim” of the color chart
-LEDs are almost pure, filtered incandescent is (usually) not
-Unfiltered incandescent light is represented by the black body curve.
-Typical tungsten bulbs have a color temperature of 2800 K, their light is yellowish (point A)
-A black body at 6500 K emits almost pure white light (point C)

Color Mixing

The intensity/flux of two light beams is specified in terms of quantities Y_1 and Y_2 and the color is specified by chromaticity coordinates x_1, y_1, x_2, y_2. The sum of the light beams is given by:

$$y_{sum} = \frac{y_1 \cdot m_1 + y_2 \cdot m_2}{m_1 + m_2}, \text{ and } x_{sum} = \frac{x_1 \cdot m_1 + x_2 \cdot m_2}{m_1 + m_2}$$

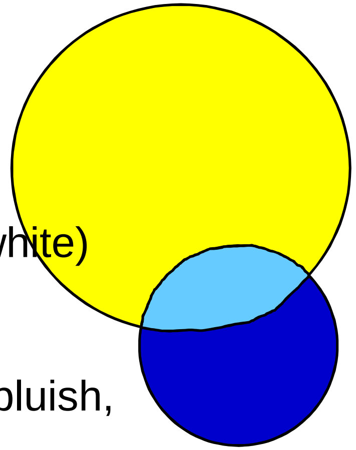
$$\text{with } m_1 = \frac{Y_1}{y_1}, \text{ and } m_2 = \frac{Y_2}{y_2}.$$

Note that $m_i = \frac{Y_i}{y_i} = \frac{X_i}{x_i} = \frac{Z_i}{z_i} = X_i + Y_i + Z_i$,

(see definition of x, y and z)

Example: Light Source 1: Y1 = 10lm; x1 = 0.1; y1 = 0.2 (yellow)
Light Source 2: Y2 = 20lm; x2 = 0.4; y2 = 0.5 (blue)

Light Source Sum: Y = 30lm; x = 0.23; y = 0.33 (bluish white)



REMARK:
Twice as much yellow flux than blue flux but it still appears bluish, because the blue is "stronger" than yellow (m1 > m2, in this particular case).

Colorimetric quantities

$$X = 683 \cdot \int P(\lambda) \cdot x(\lambda) \quad d\lambda$$

$$Y = 683 \cdot \int P(\lambda) \cdot y(\lambda) \quad d\lambda \quad (\Rightarrow \text{intensity [cd]})$$

$$Z = 683 \cdot \int P(\lambda) \cdot z(\lambda) \quad d\lambda$$

$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z}$$

$$z = \frac{Z}{X + Y + Z}$$

$$x + y + z = 1$$

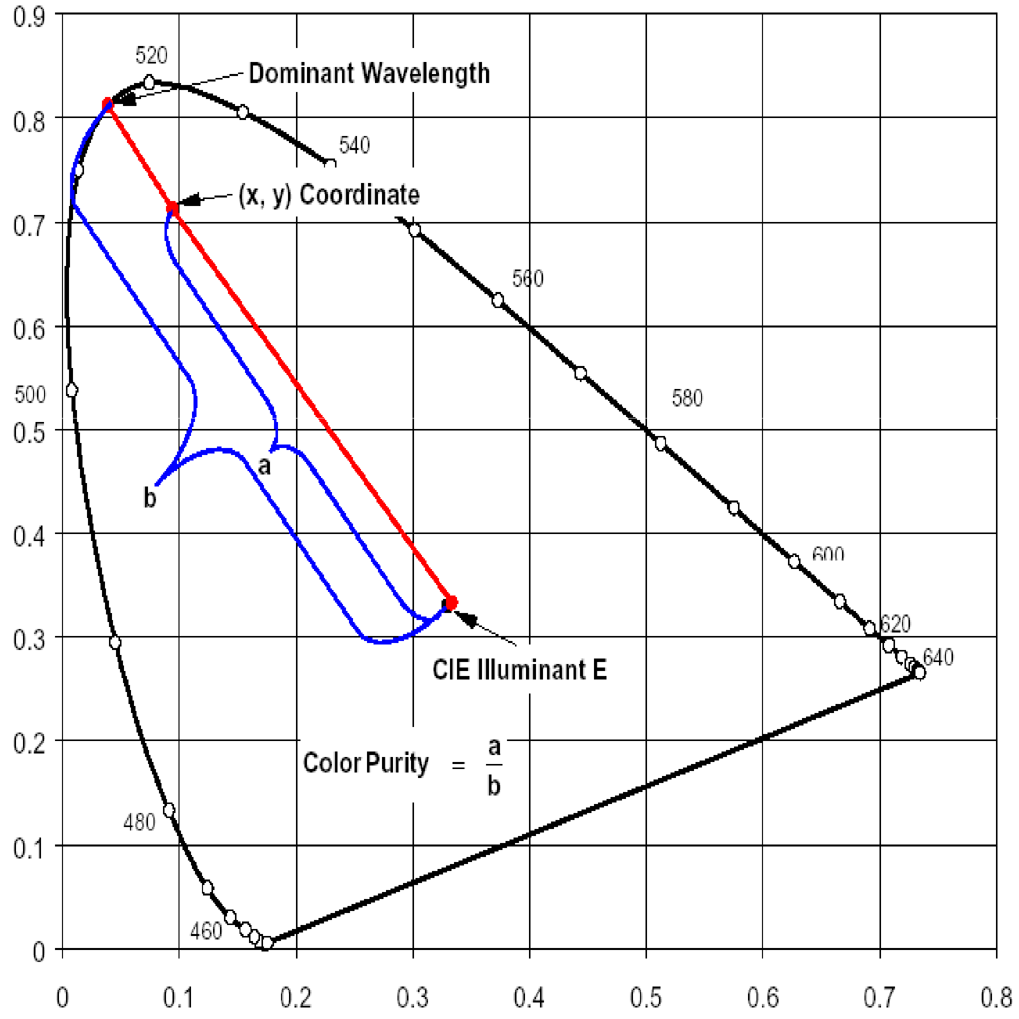
P(λ) is the radiated spectrum of the light source
(i.e. the spectral intensity of the source)

x(λ), y(λ) and z(λ) are the CIE color matching functions
(sometimes also called x-bar, y-bar and z-bar)

X, Y and Z are the colorimetric quantities
(Y is equal to the photometric intensity)

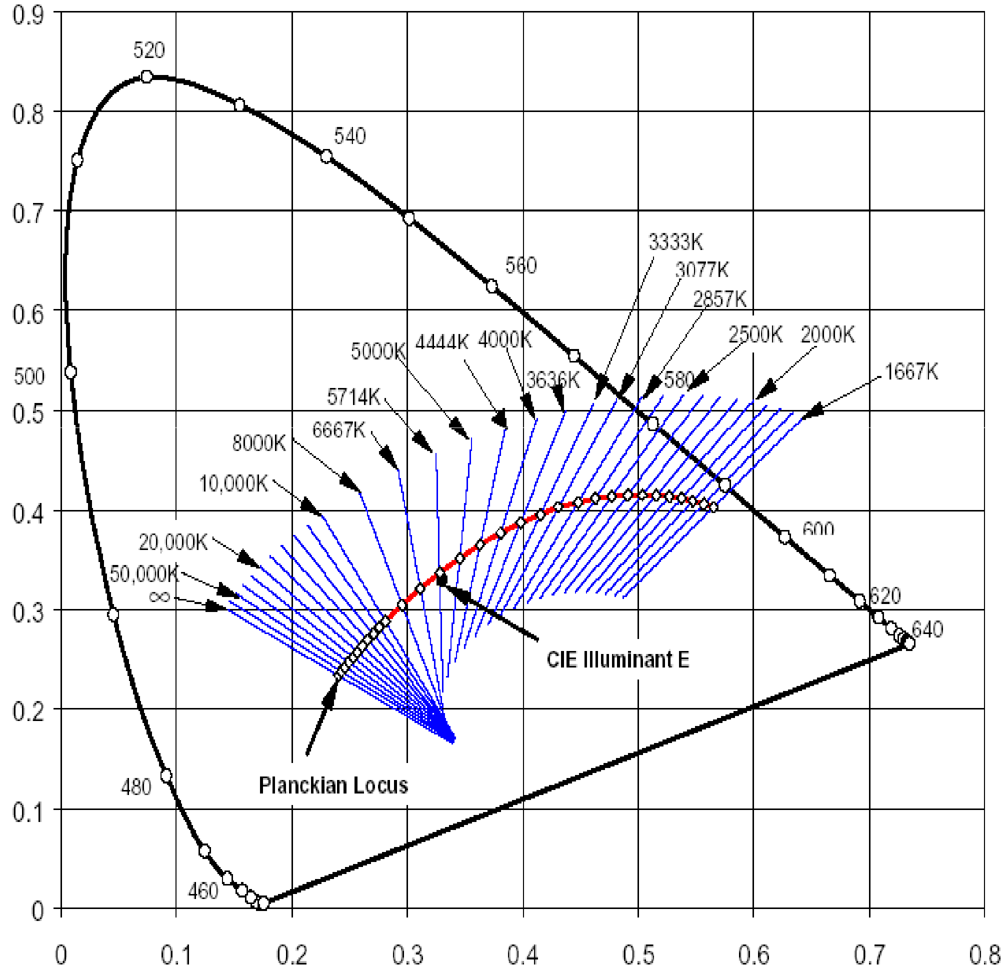
x, y and z are the color coordinates
(x and y are the coordinates in the CIE-Diagram)

Color Purity



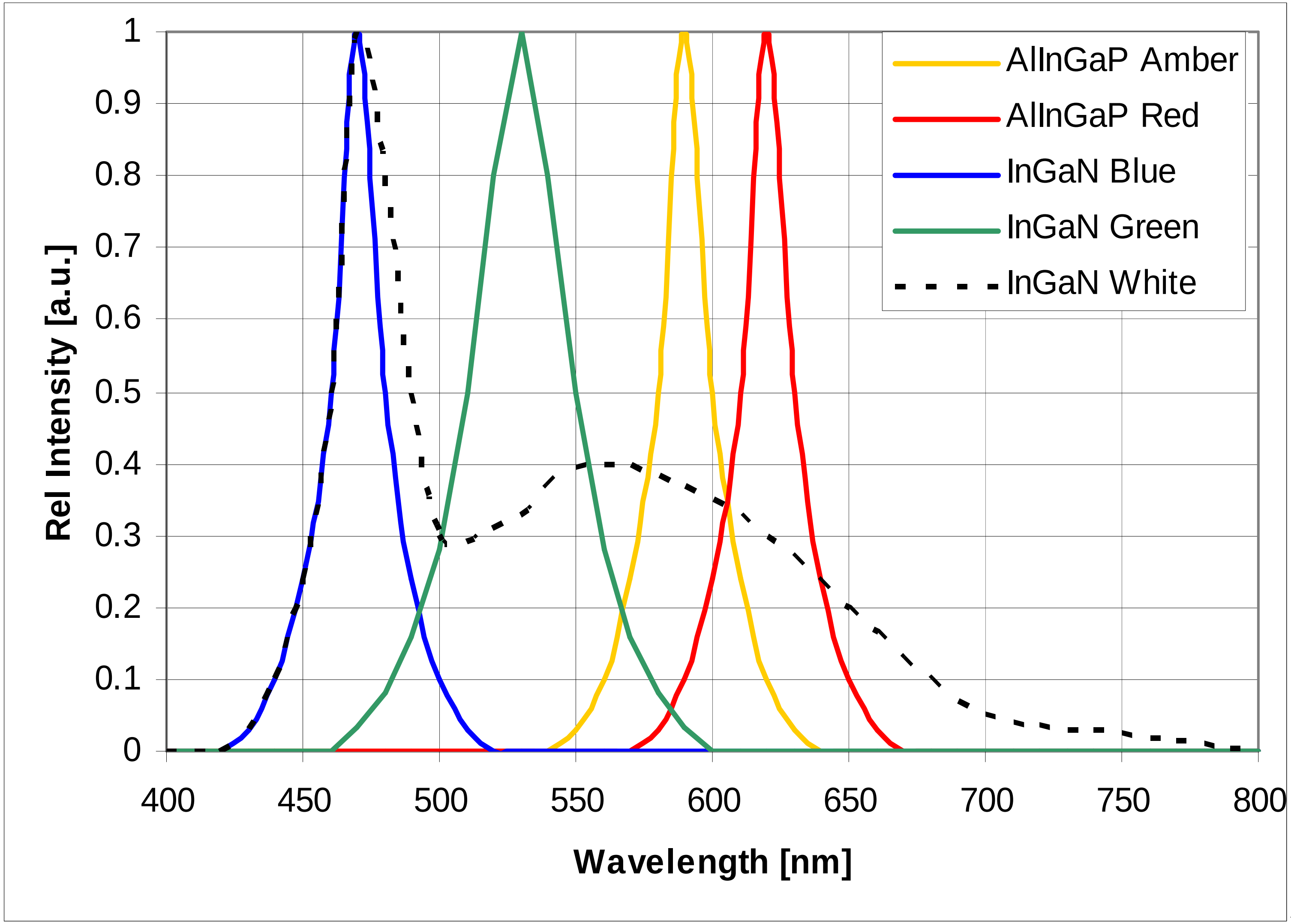
- Color Purity defines "how far away" a color is from it's corresponding pure color
- Reference is Illuminant E(0.333,0.333)
- Color Purity= a/b

Correlated Color Temperature

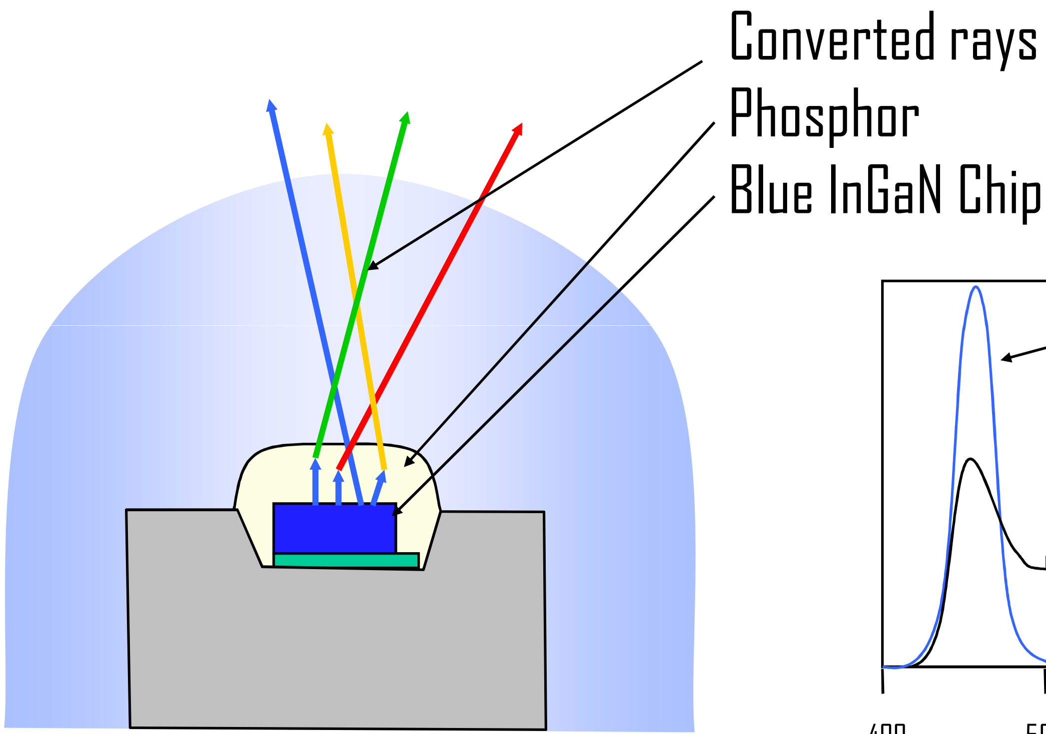


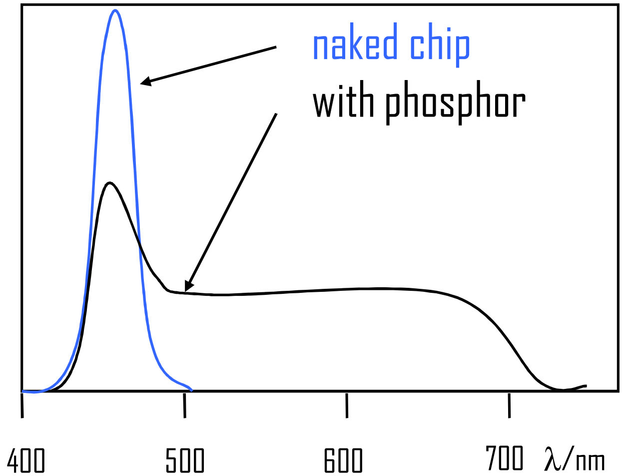
- Correlated Color Temperature (CCT) is the temperature of a black body source most similar in color to a source in question
- Only applicable for sources close to the black body curve (white light)

Typical LED Spectra



InGaN white LED Structure



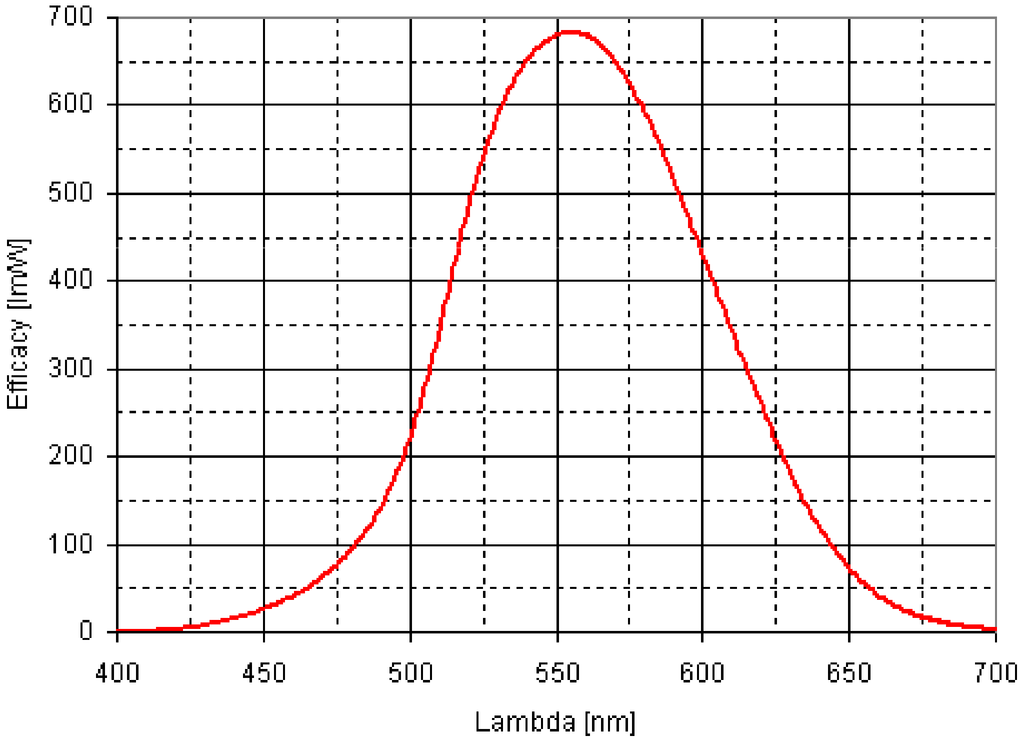


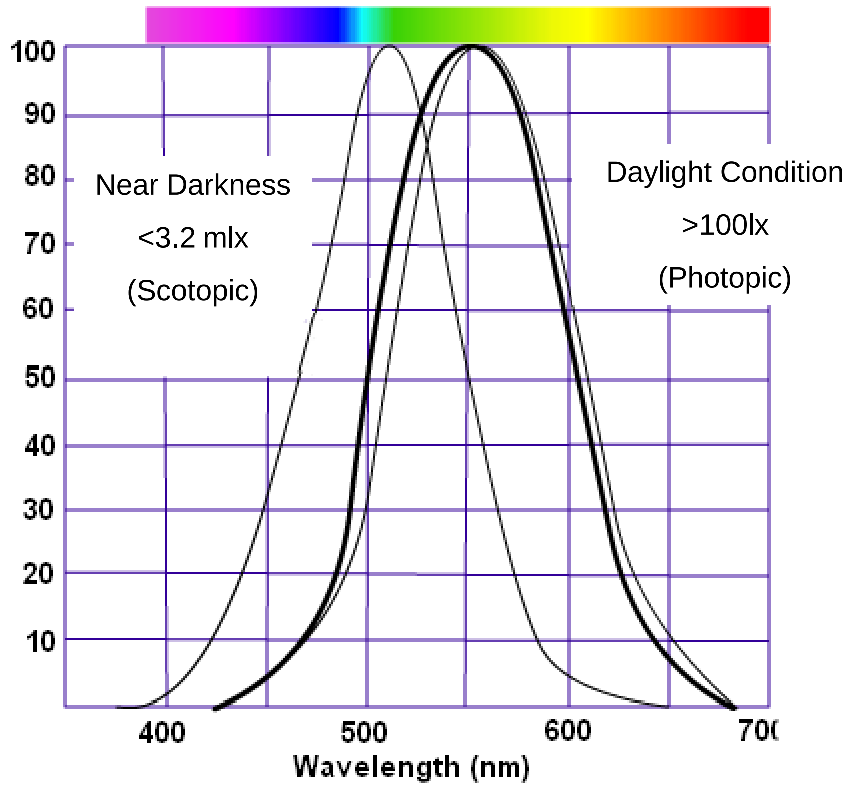
The Human Eye Response

- All radiation which can be see with the eye is considered light (approx. 400nm to 750nm)
  - **Radiation** is measured in radiometric units, and
  - **Light** is measured in photometric units.
- The sensitivity of the eye is dependant on the wavelength of the light (e.g. the eye is 10,000 times more sensitive to 555nm-Green than to 750nm-Red).
- The response of the eye is logarithmic (high dynamic range).
- The average human eye can only see the difference of a factor of two to one in intensity (the eye is a bad detector).

Eye Response

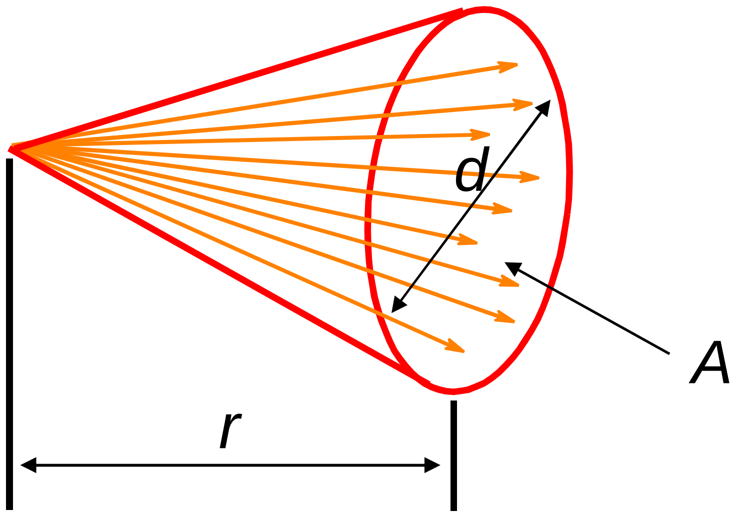
LIGHT PRESCRIPTIONS INNOVATORS





In most night vision cases (night traffic, etc), the eye is in an intermediate state between scotopic and photopic called “mesopic” vision

Intensity I and Solid Angle Ω



Definitions:

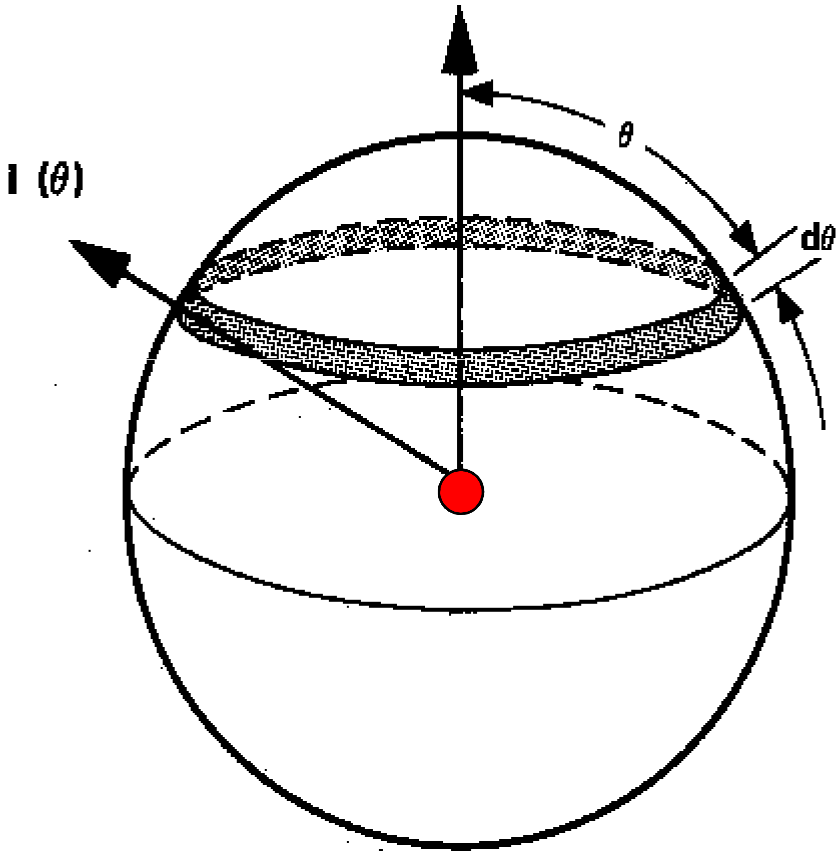
$$I = \frac{d\Phi}{d\Omega}$$

for d << r :

$$\Omega = \frac{A}{r^2} = \frac{\pi d^2}{4r^2}$$

Radiometric Intensity:	I_v	[W/sr]
Photometric Intensity:	I	[lm/sr] or [cd], Candela
Solid Angle Units:	Ω	[sr], Steradian

Conversion from Intensity to flux



Flux in the far field of a source emitted into a solid angle element:

$$d\Phi = I(\theta,\varphi)d\Omega$$

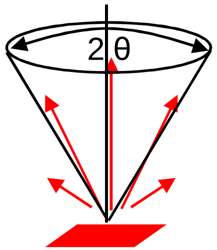
Rewrite in integral Form:

$$\Phi = \int\int I(\theta,\varphi)\sin(\theta)d\theta d\varphi$$

Total Flux for rotational Symmetry:

$$\Phi = 2\pi\int_0^{\pi} I(\theta)\sin(\theta)d\theta$$

Lambertian Emitter



Typical radiation pattern of a flat surface :
(i.e. LED chip top surface)

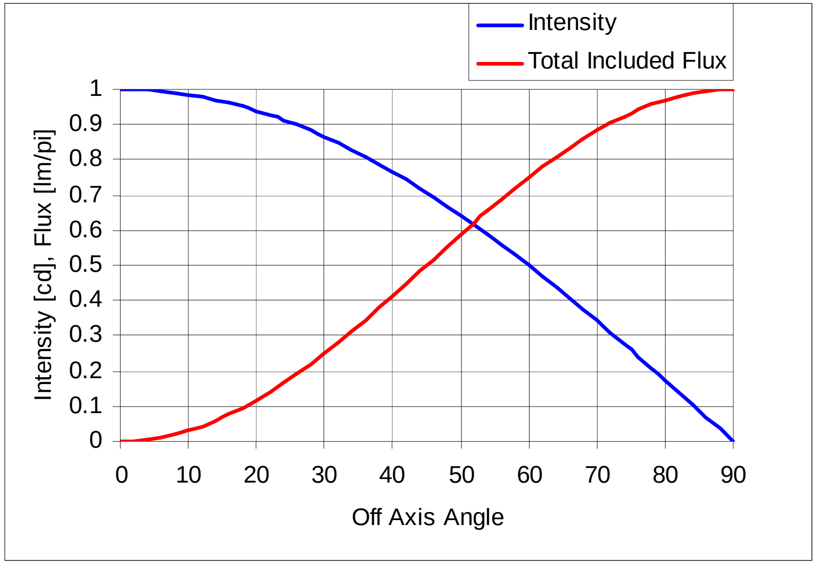
$$I(\theta) = I_0 \cos(\theta)$$

Total flux in a cone with an opening angle 2 θ:

$$\Phi = 2\pi \int_0^\theta I(\theta')\sin(\theta')d\theta'$$

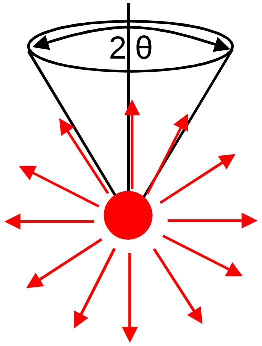
$$= 2\pi \int_0^\theta I_0 \cos(\theta')\sin(\theta')d\theta'$$

$$= \pi \sin^2(\theta) I_0$$



The total flux of a Lambertian source of 1 cd on axis is π lm!
To collect for example 90% of the Flux of a Lambertian source, the optics must capture a cone ±72 deg off axis angle

Uniform Emitter



Typical radiation pattern of a spherical surface (i.e. the sun), or of, as a rough approximation, an incandescent filament.

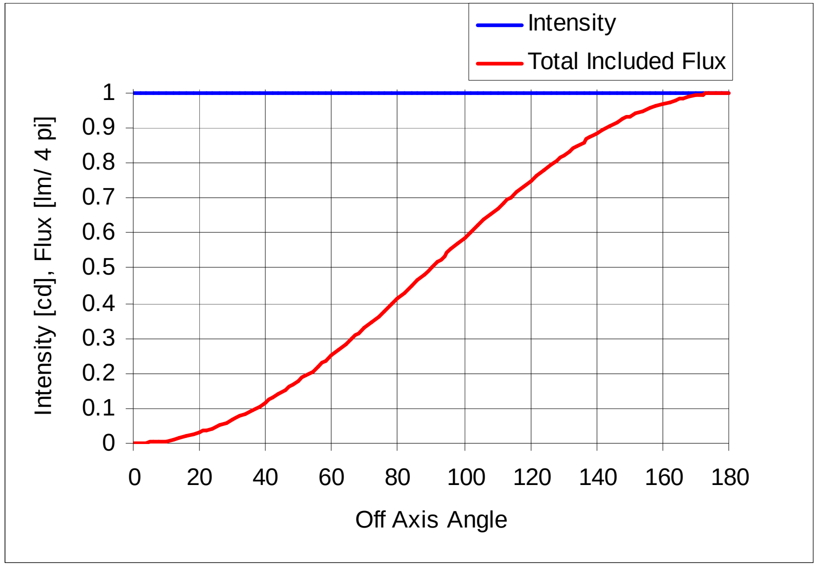
$$I(\theta) = I_0 = const$$

Total flux in a cone with an opening angle 2 θ:

$$\Phi = 2\pi \int_0^{\theta} (I(\theta')\sin(\theta')d\theta'$$

$$= 2\pi \cdot I_0 \int_0^{\theta} \sin(\theta')d\theta'$$

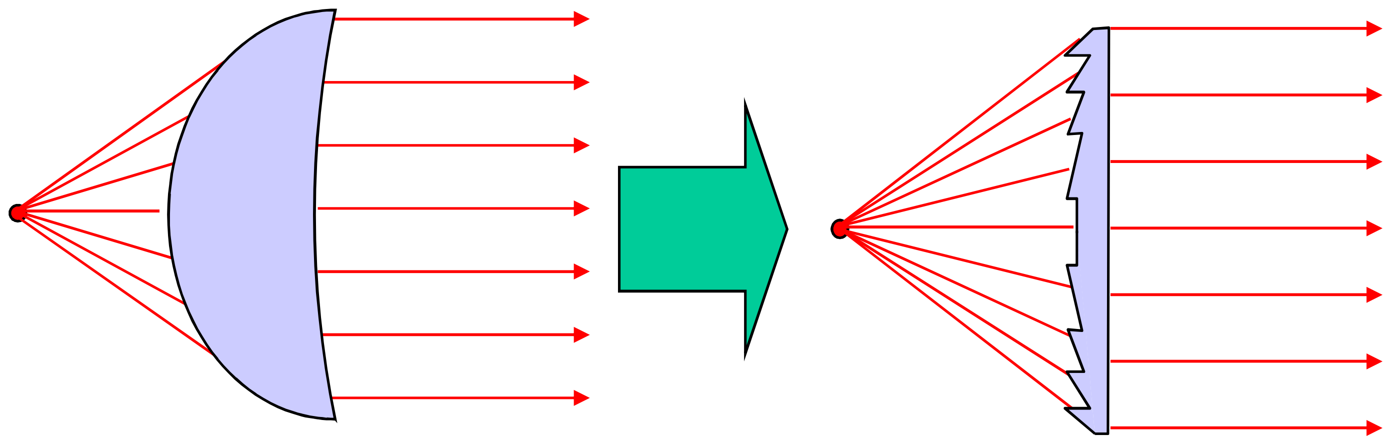
$$= 2\pi \cdot I_0 (1 - \cos(\theta))$$



The total flux of a uniform source (integral from 0 to 2 pi) of I_0 =1 cd is 4π lm!

Fresnel Lenses

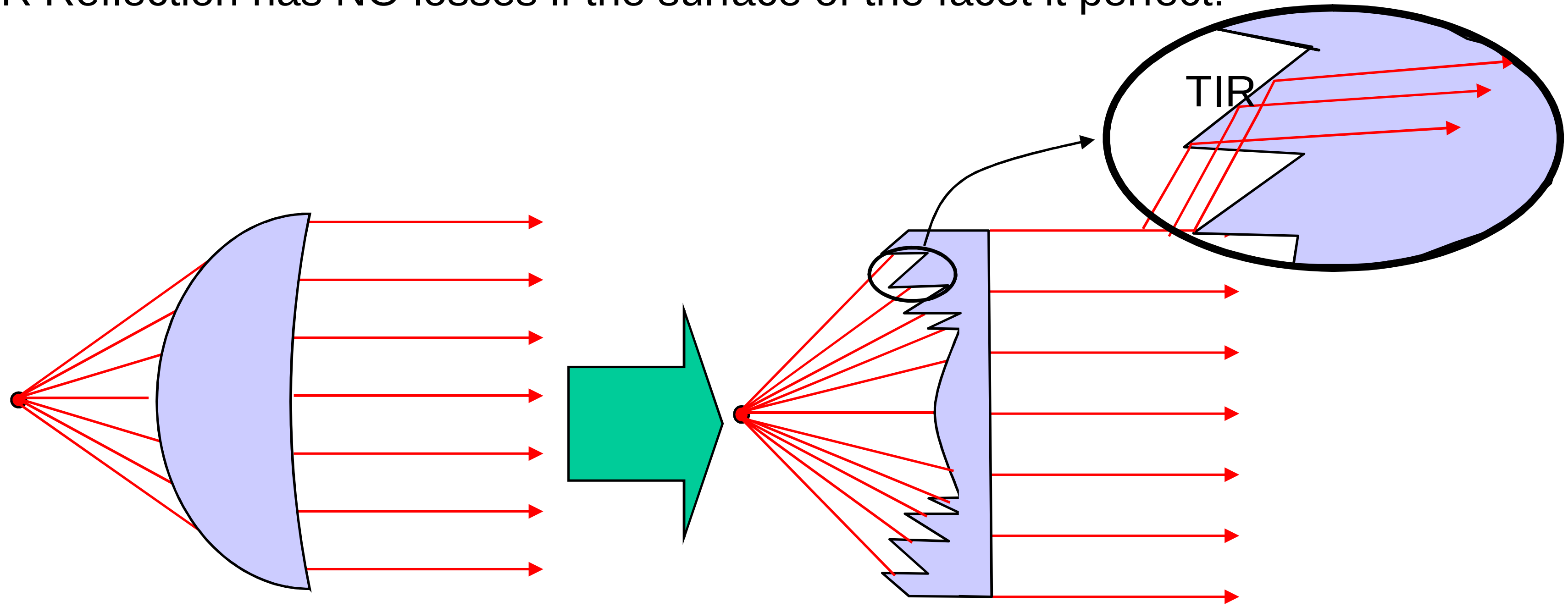
-For collimating light
-To make a conventional lens “thinner”
-Works only by refraction
-Fresnel “teeth” can be on the in- and outside of lens
-Not very efficient for large off-axis angles



Conventional lens   fresnel lens

TIR Lenses

-For collimating light
-To make a conventional lens “thinner”
-Works by refraction AND total internal reflection
-“Teeth” are on the inside of lens
-Very efficient for large off-axis angles, no so efficient for small angles
-TIR Reflection has NO losses if the surface of the facet it perfect!

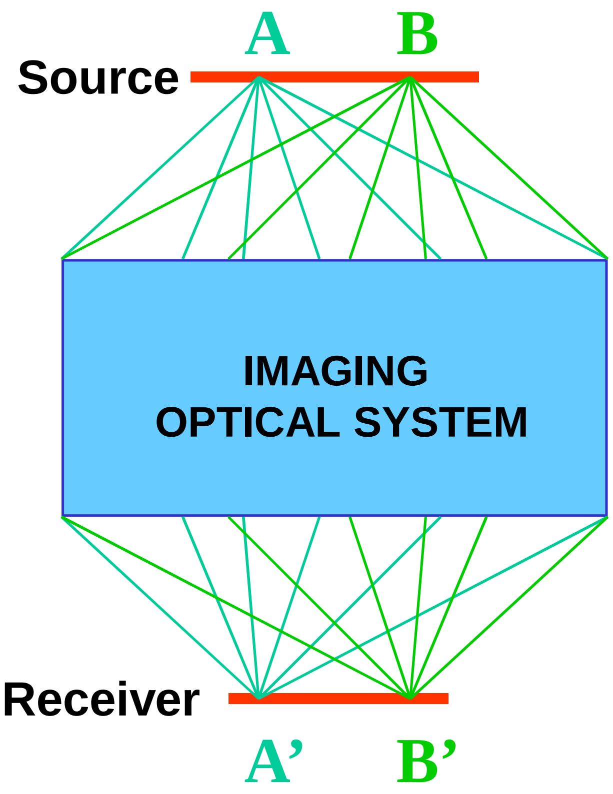


Conventional lens

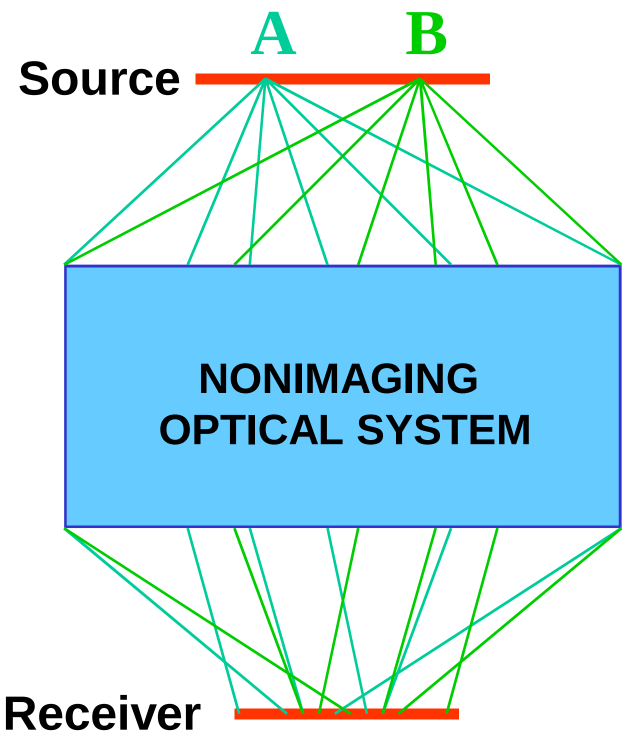
TIR lens

Nonimaging Optics (NIO)

NIO → **optimum transfer of luminous power**

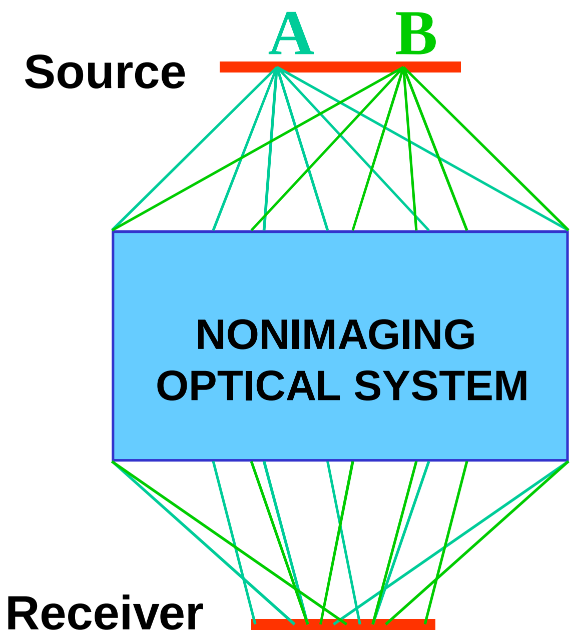


Source image



No Source image

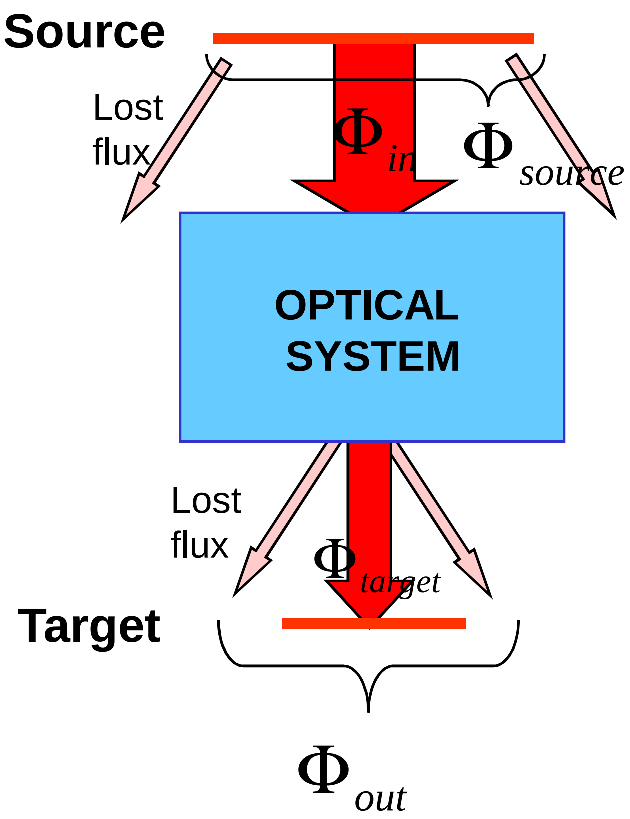
NIO Design Rules



Basic conservation and design rules:

- Flux conservation
- Etendue conservation
- Luminance conservation
- Edge ray principle

Flux Conservation and Efficiency



Flux conservation:

A passive optical system always decreases the source flux due to absorption and reflection losses within the optical system:

$$\Phi_{out} \leq \Phi_{in}$$

Collection Efficiency:

The collection efficiency is the fraction of the source flux captured by the optical system

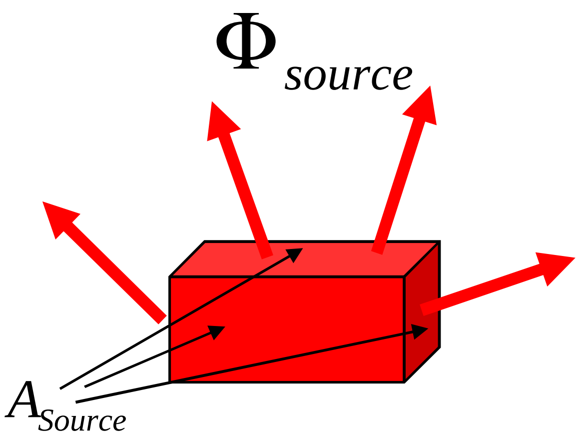
$$\eta_{coll} = \Phi_{in} / \Phi_{source}$$

Optical Efficiency:

The optical efficiency of a system depends on the definition of the "useful" flux that falls onto the desired target (either a surface or far field angle interval).

$$\eta_{opt} = \Phi_{target} / \Phi_{source}$$

Illuminance



Illuminance [Lux]:

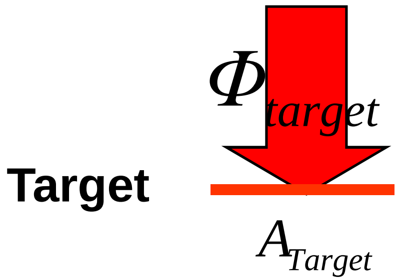
$$E = \frac{d\Phi}{dA}$$

"Flux emitted by a surface element"

Average Source Illuminance:

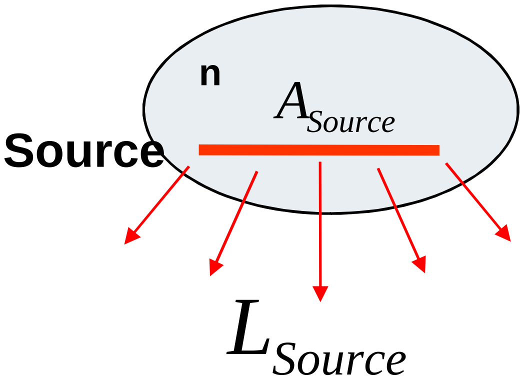
$$E = \frac{\Phi_{Source}}{A_{Source}}$$

Example: A 100 lm 1x1 mm² LED chip has a total emitting surface of typically 2 mm² (including it's 4 lateral surfaces!) => E=50 lm/mm²
Typical values for a filament: 50 lm/ mm²



"Flux received or emitted by a surface element"
Sun: 10-100000 lx
Received by surface:
Desktop illumination: 500 lx
ECE LB: 6 lx, HB: 32 lx @ 25 m

Luminance



Luminance [cd/m²]:
"Perceived brightness of a source"

$$L = \frac{dI}{dA}$$

"Intensity emitted or
received by a surface element
Or
flux per surface and solid angle"

Average Source Luminance for Lambertian sources:

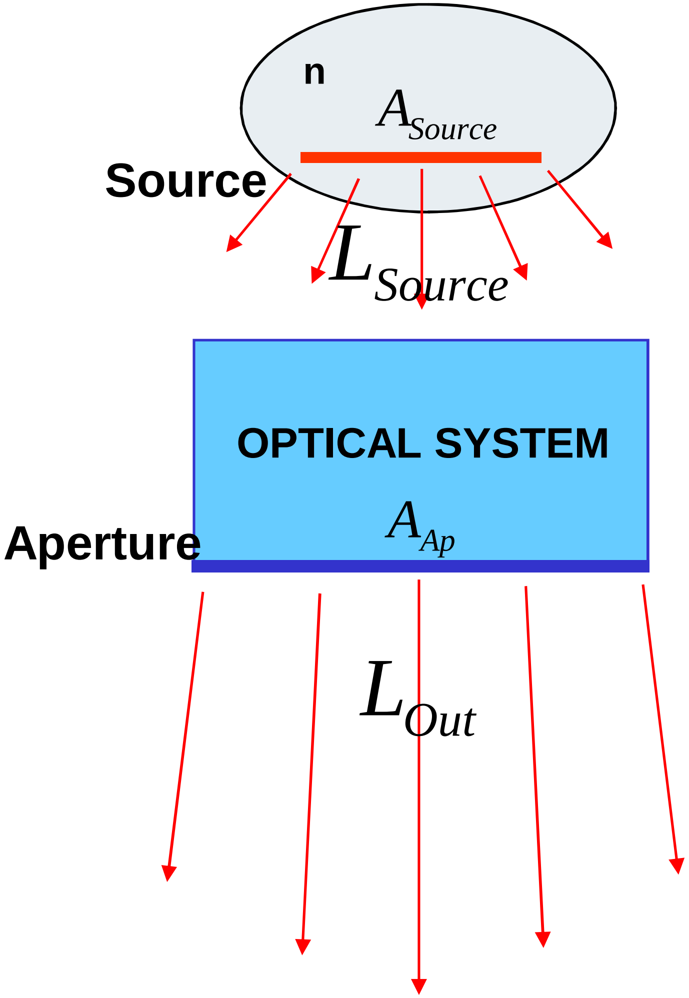
$$L_{Source} = \frac{E_{Source}}{n^2 \cdot \pi} = \frac{\Phi_{Source}}{A_{Source} \cdot n^2 \cdot \pi}$$

If the source emits into a full hemisphere, the second half of the equation holds. L in general is a function of angle. L is constant for lambertian sources

With the index of refraction (n) of medium surrounding the source

Typical values for a filament bulb (n=1): 5-20 cd/ mm^2
Good bulb (automotive halogen): approx. 25 cd/ mm^2
White LEDs: up to: 100 cd/ mm, constantly improving
Sun: 1500 cd/ mm^2

Luminance Conservation



Luminance Conservation:

$$L_{out} = t \cdot L_{Source}$$ "Conservation of brightness"

No optical system can increase the brightness of a source*.

Transmittance t takes into account all reflective and absorptive losses of "central" rays contributing to the hot spot.

Minimum Optics Aperture Size for Hotspot:

$$A_{Ap} \geq \frac{I_{max}}{t \cdot L_{Source}}$$

A "real" aperture, that is not totally flashed as seen from the hotspot will have to be larger!

Example: Desired Intensity: 1000 cd, source luminance: 2.1 cd / mm^2, t=0.7: A_{ap}>680 mm^2

*A system that adds up different colors into the same light path (by dichroic mirrors) and light recycling systems (like BEF films) are the only exceptions

Far Field Definition for lambertian sources

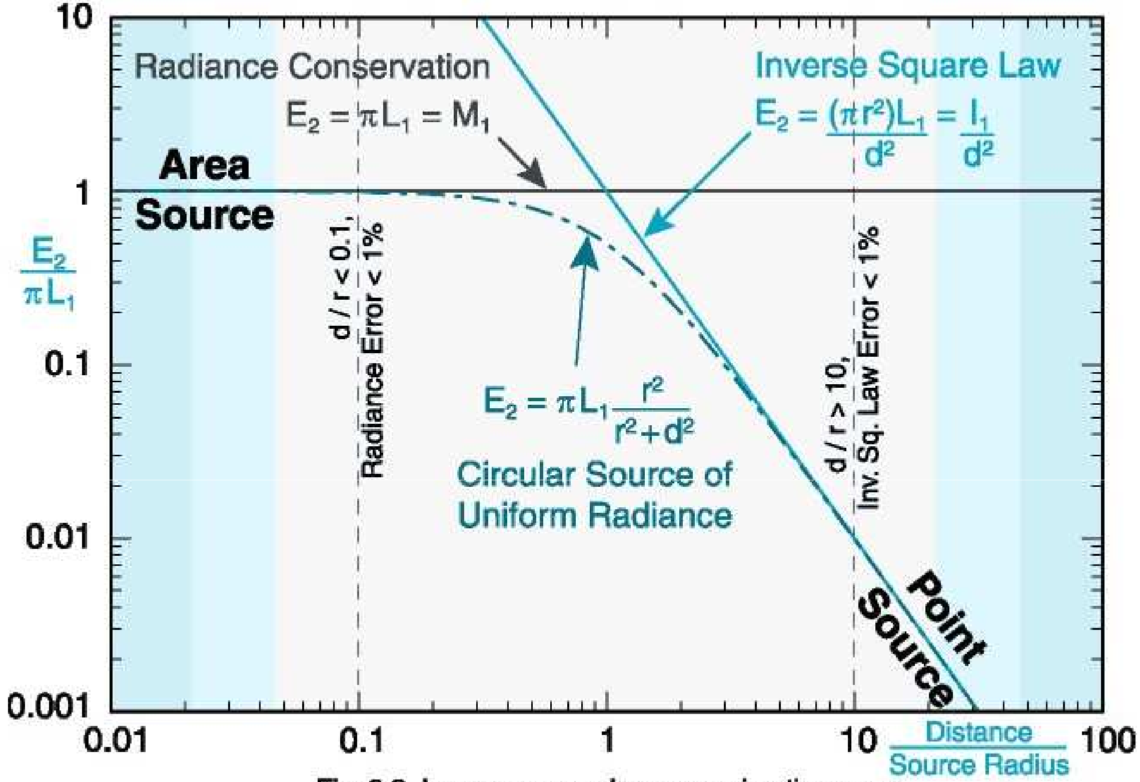


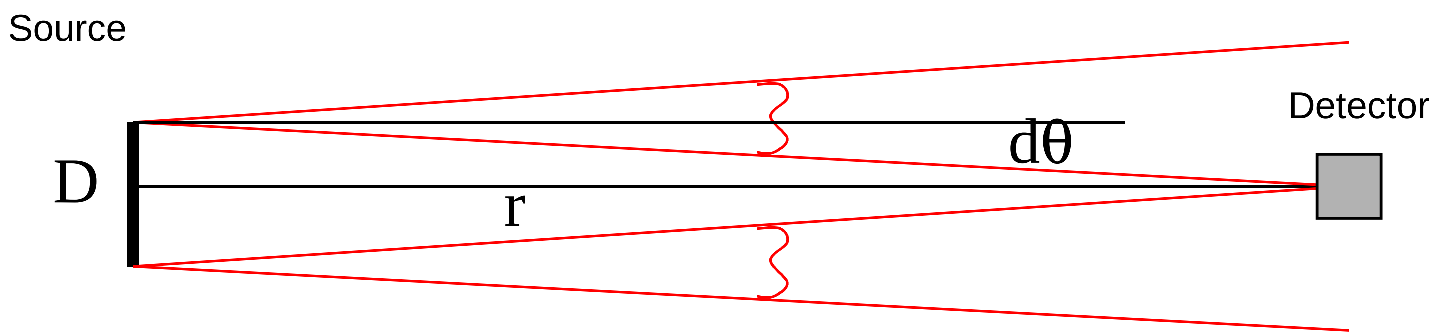
Fig. 6.2 Inverse square law approximation error.

Lambertian source of radius r with a detector of the same radius at distance d. The source is supposed to have uniform radiance, (luminance) so L1. To the far field intensity is pi r^2 L1 and the signal at the detector E2= I1/ d^2

The signal of the very close to the source is the full flux from the source. The transition from near to far field is from d/r=0.1 .. 10.

In the limit of a perfectly collimated source, the detector signal is independent from the distance, so that the near field extends to infinity.

Far Field Definition for peaked sources



To see detail in a pattern with a resolution of dθ, the detector has to be at a distance of at least: R>D/(2 tan(dθ)). This insures that light emitted with dθ from any point of the source (the extreme edges) hits the detector

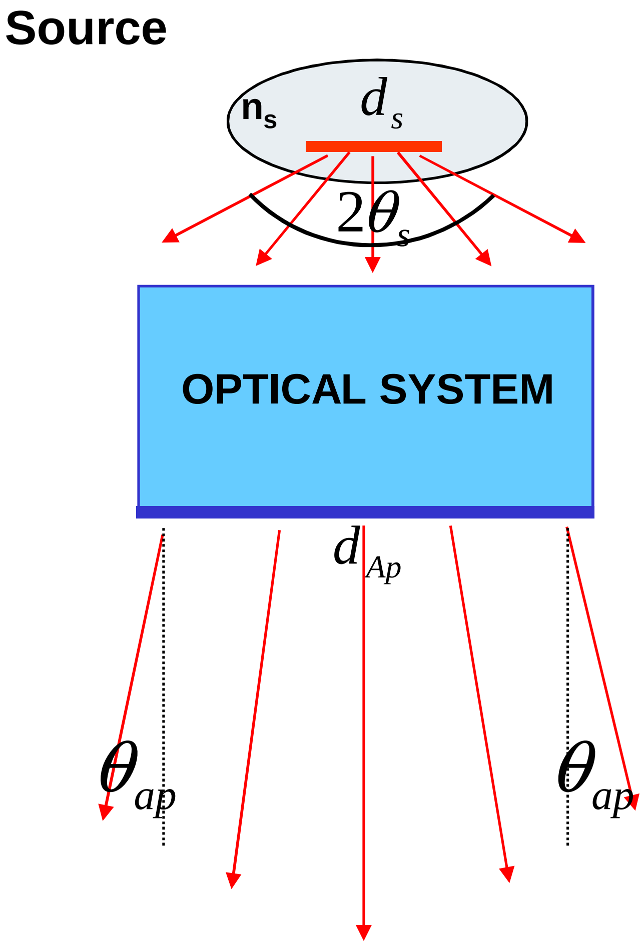
Examples:

D=50 mm, dθ=1 deg => r> 1.4 m

D=50 mm, dθ= 0.2 deg => r> 7 m

D= 100 mm, dθ= 0.1 deg => r> 28 m (automotive headlamp)

Etendue Conservation, Simplified



Etendue in 2 Dimensions

$$E = 2 \cdot d \cdot n \cdot \sin(\theta)$$

Sometimes called luminosity, light-gathering power or acceptance.

The Etendue in an optical system is conserved.

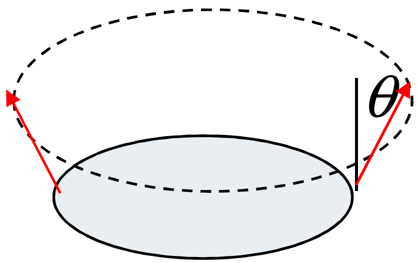
$$\Rightarrow d_{ap} = d_s \cdot \frac{n_s \sin(\theta_s)}{n_{ap} \sin(\theta_{ap})}$$

Formula can be used in the horizontal and vertical direction independently.
Example: Desired exit angle θ_{ap}=5º (half angle!), d_s=1 mm, n_s=1.5, n_{ap}=1, θ_s=90º (collect full LED flux) => minimum aperture width: d_{ap}=17 mm

A smaller aperture can yield the same collimation angle θ_{ap}- if the collection angle θ_s is reduced. =>

Too small aperture + too small collimation angle => low efficiency

Etendue 3D, simplified



Source, A

Etendue in 3 Dimensions,
rotational symmetric emission

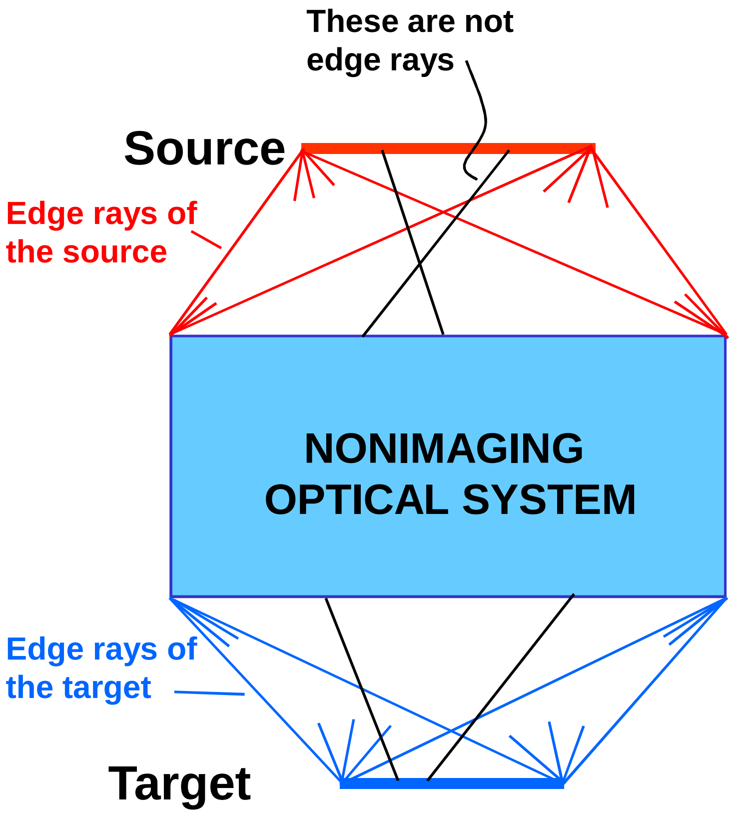
$$E = \pi \cdot n^2 \cdot \sin^2(\theta) \cdot A$$

Assumes that all light emitted is confined in a cone
of 2x the opening angle theta

Etendue in 3 Dimensions,
rotational symmetric emission in limited angle cone,
2D formula does not apply in this case!

$$E = \pi \cdot n^2 \cdot (\sin^2(\theta_1) - \sin^2(\theta_2)) \cdot A$$

Edge Ray Principle



The Edge Ray Principle

Rays emerging (impinging) from the edge of a source and/ or under the maximum angle to a reference surface are called **edge rays**.

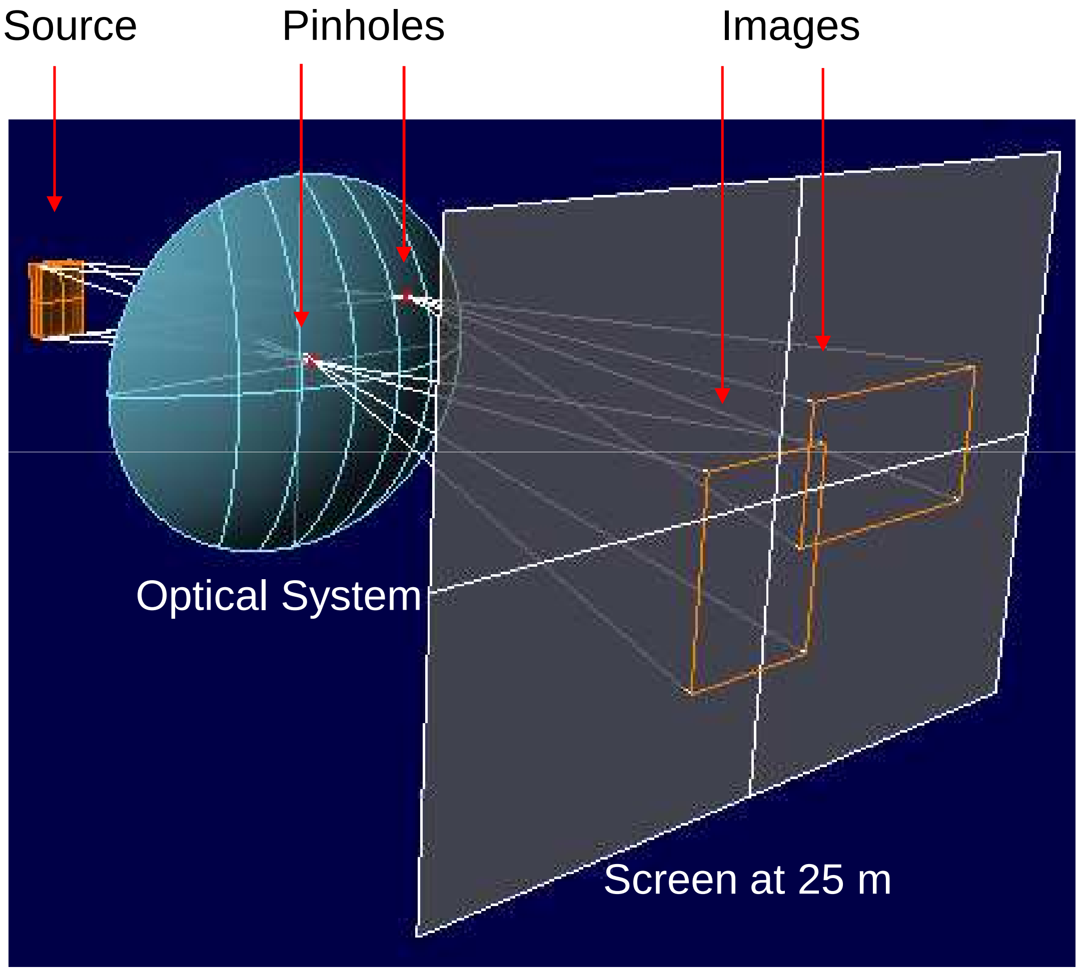
The edge-ray principle states that, in order to couple an emitted ray bundles by means of an optical system to a target ray bundle, it is sufficient to connect the edge-ray subsets.

In simpler words:
If the optical systems is designed to transmit the source edge rays to the target, all other rays will also hit the target.

Source Image Superposition

Superposition Principle:

A Far Field Intensity pattern can be understood as a superposition of far field images of the source (although this imaging not always occurs) through pinholes at exit surface.



Simultaneous Multiple Surface (SMS) technology

LIGHT PRESCRIPTIONS INNOVATORS

- The **SMS** method is the most recent and advanced design tool in NIO
- The **SMS** method provides devices that perform close to the theoretical limits: prescribed intensity patterns achievable with the maximum efficiency
- It uses the principles of refraction (**R**), reflection (**X**) and TIR (**I**) in optical elements
- It numerically creates at least two surfaces at the same time

- **LPI is holding several patents that protect the SMS method**

Example

In the following slides a typical Free-Form-Optics design problem is introduced to compare conventional methods to the SMS method:

“Generation of a prescribed Far Field Radiation pattern from a known light source (incandescent, LED, HID…)”

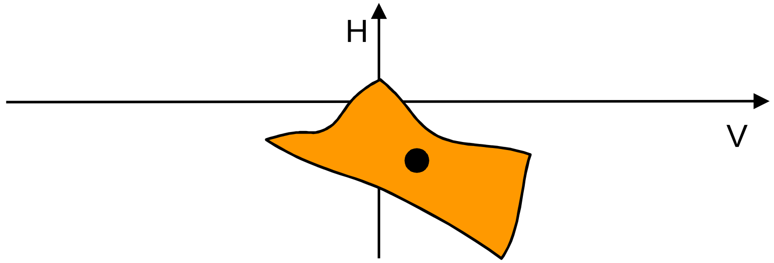
Typical application: Car Head lamps

Conventional Free From Design Methods

- Creates **one** free-from surface (= reflective or refractive surface, others can be “chosen”)
- Can be solved either by iterative procedures or by solving non-linear differential equation
- Allows to produce a desired radiation pattern for a **Point Source**
- Extended source will produce different radiation pattern
  => repeat the design process with a different point source target radiation pattern until extended source radiation pattern is “good”

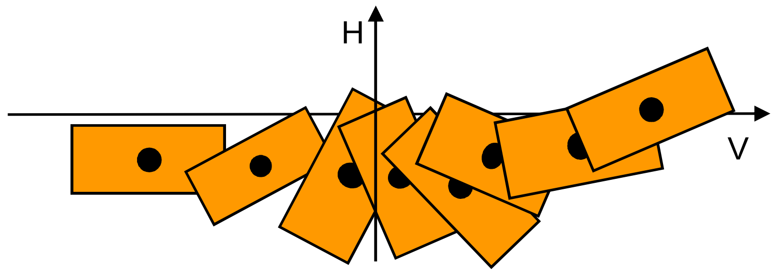
Conventional Free From Design Methods

- Design controls only the position of **one** point of the source image (center, edge or corner) but not it's size and shape



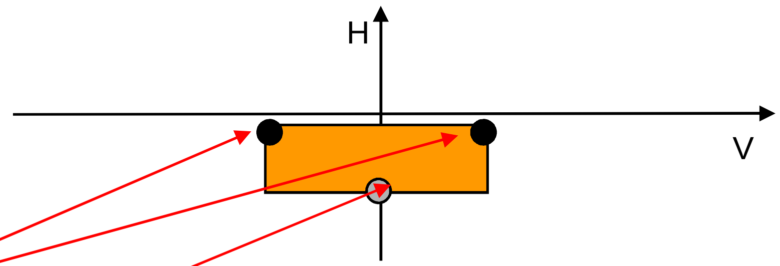
- Single Free Form Reflector design: The image of the source **always** rotates

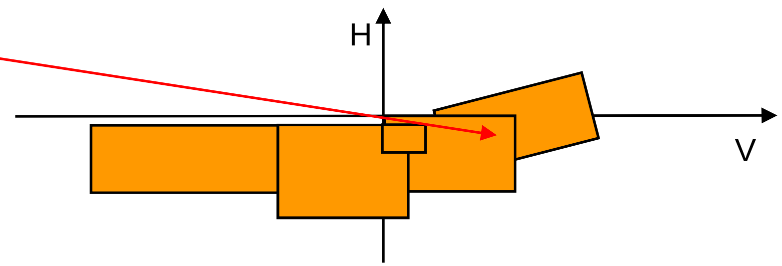
  ⇒ large vertical spread



3D-SMS DESIGN

- Method generates at least two free-form surfaces at the same time (refractive or reflective, more surfaces can be "chosen")
- Two design points guide extended source image
- Gives control of vertical image size
- Gives full control over image width and rotation
- Produces minimum vertical spread, no rotation, optimized pattern estetics





Comparison Conventional/ SMS

	Conventional	**SMS**
Number of surfaces created:	One	Two (or more)
Source model:	Point Source	Extended Source
Image Rotation control:	No	Yes
Image Size control:	No	Yes
Optics Aperture Size:	Large	Close to physical limit
Optics Depth	Deep (?)	Can be minimized
Efficiency:	?	Up to 85%

Machband Effect

- The Machband describes an effect where the human mind subconsciously increases the contrast between two surfaces with different luminance=> good for distinghuising objects and detecting illuminance steps
- Mach banding is caused by lateral inhibition of the receptors in the eye. As receptors receive light they draw light-sensitive chemical compounds from adjacent regions, thus inhibiting the response of receptors in those regions.