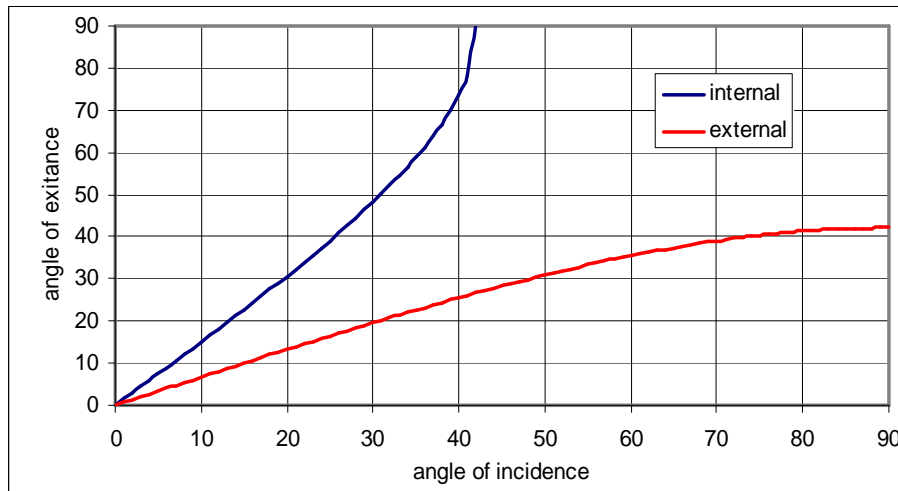
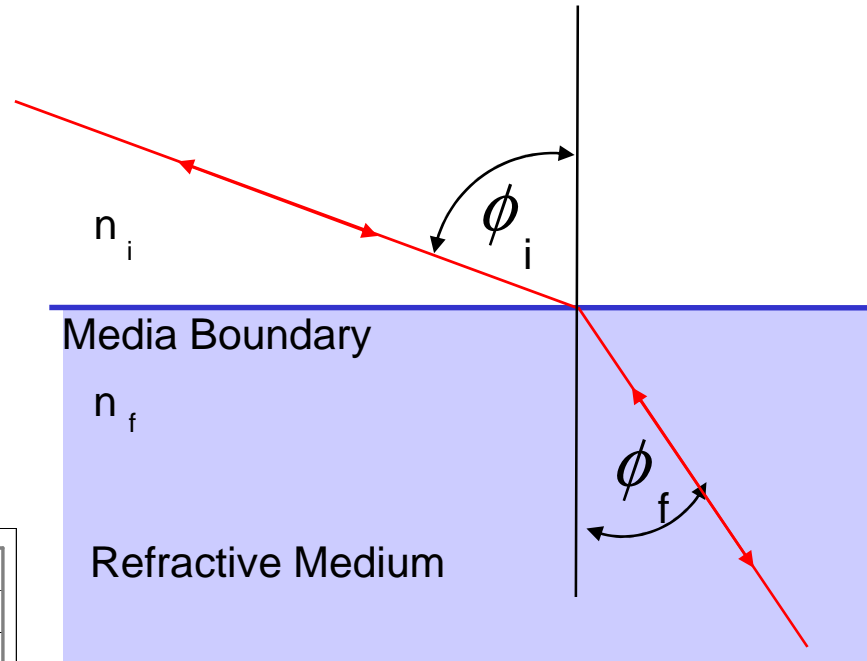


# Basic Optical Concepts

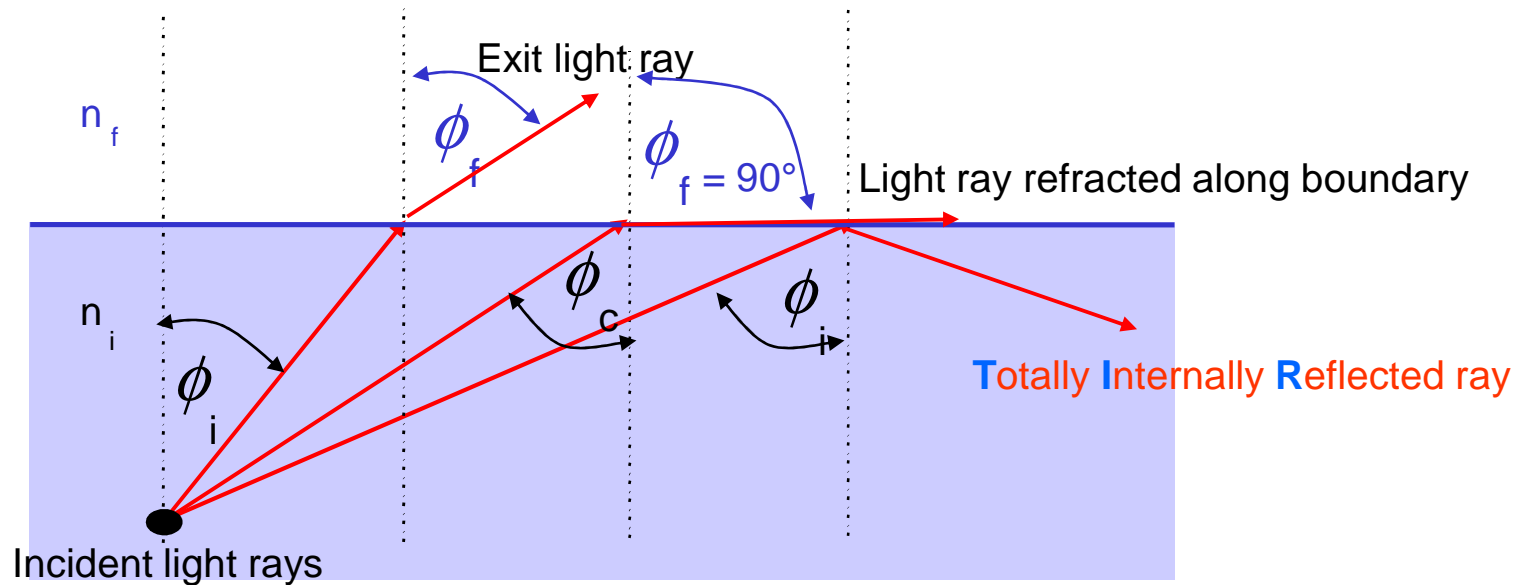
# Refraction- Snell's Law

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):

$$\phi_c = \text{Arcsin}(1/n) = 42^\circ$$

(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:

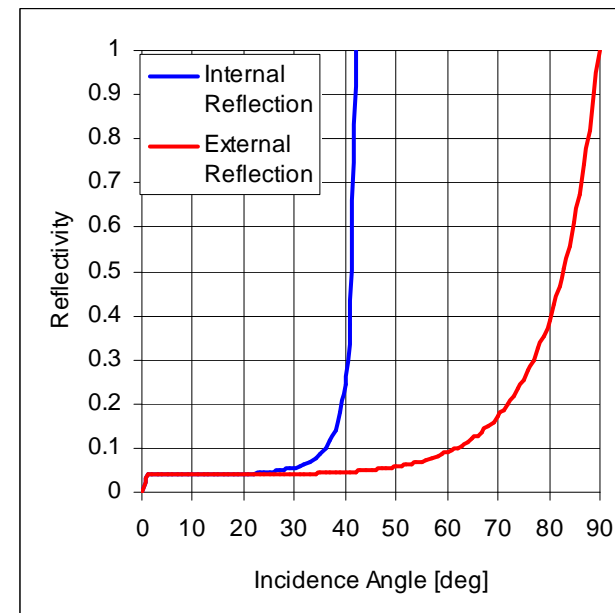
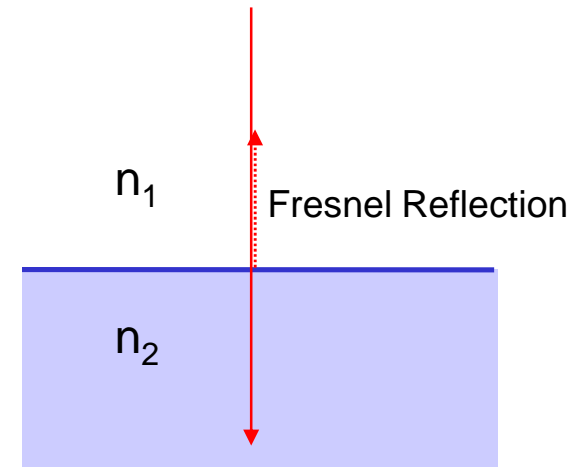
- TIR is the most efficient reflection:  
An optically smooth interface has 100% reflectivity
- Metallization: Al (typical): 85%, Ag (typical): 90%

## Refraction:

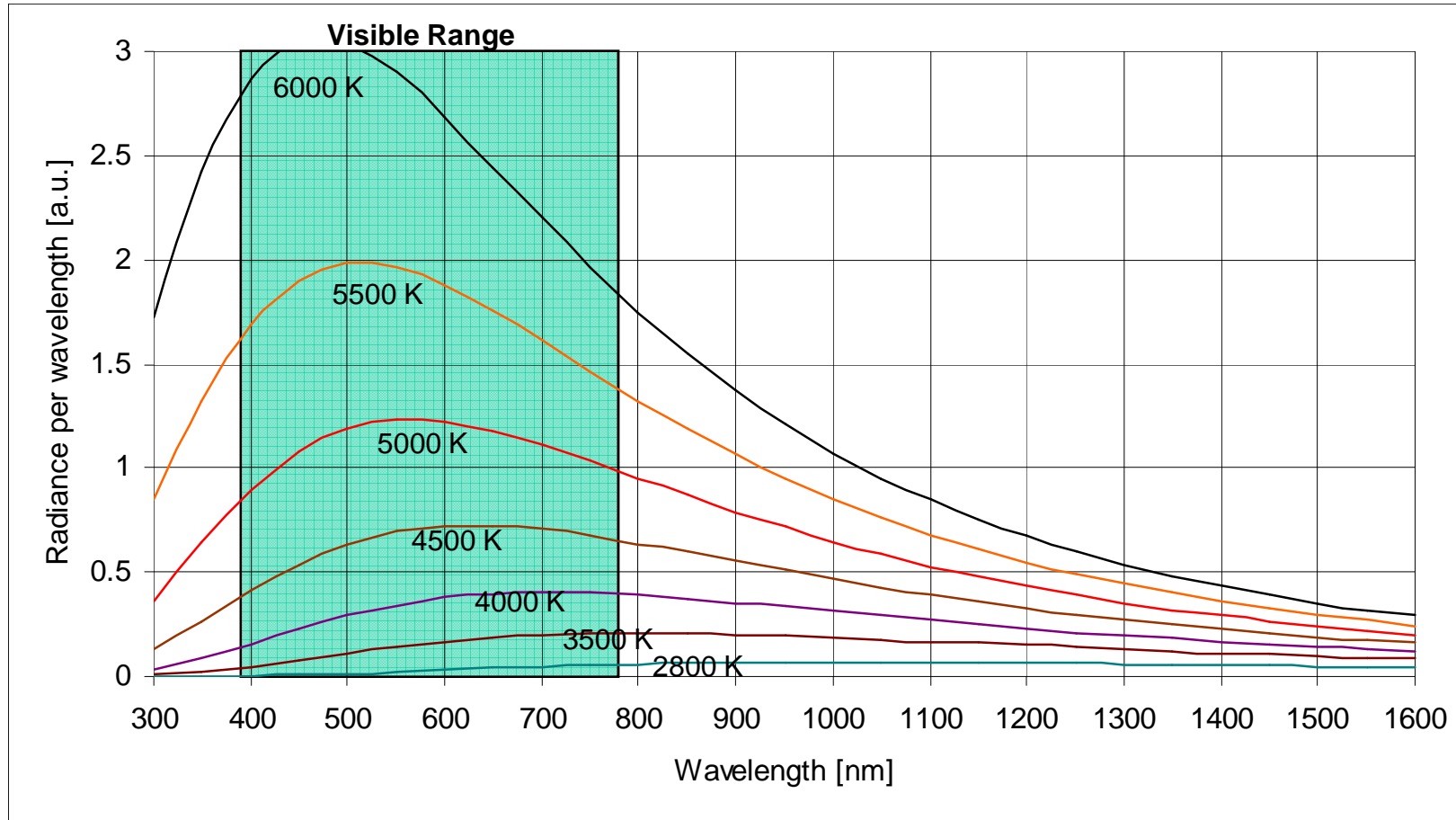
- There are light losses at every optical interface
- For perpendicular incidence:

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

- 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:  $T_{\text{tot}} = T_1 * T_2 * T_3 \dots$
- For a flat window:  $T = 0.96^2 = 0.92$
- For higher angles the reflection losses are higher

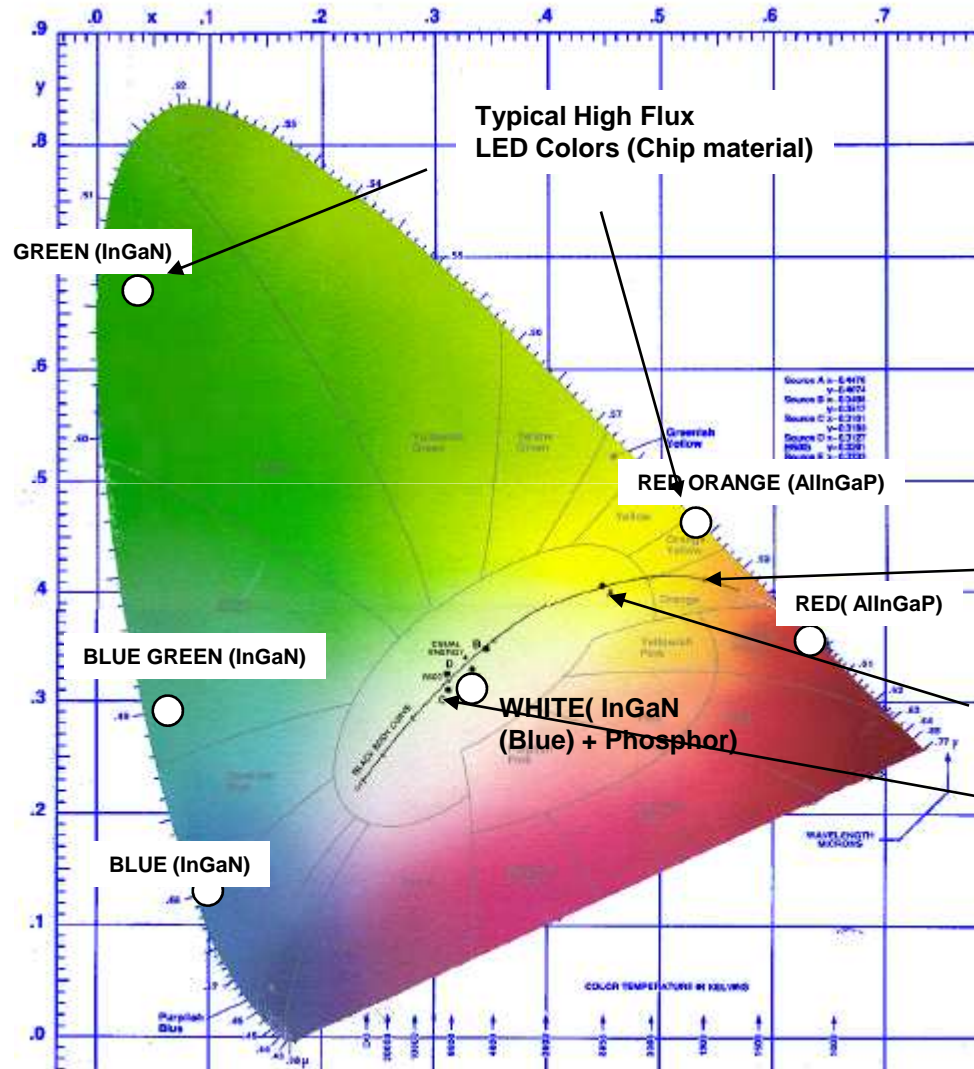


# Black body radiation & Visible Range



- 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 one 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  $m_i = \frac{Y_i}{y_i} = \frac{X_i}{x_i} = \frac{Z_i}{z_i} = X_i + Y_i + Z_i$ ,

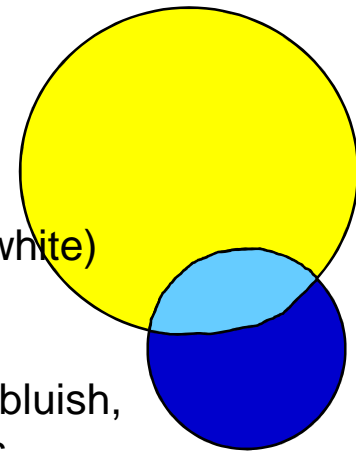
(see definition of  $x, y$  and  $z$ )

**Example:** Light Source 1:  $Y_1 = 10\text{lm}; x_1 = 0.1; y_1 = 0.2$  (yellow)  
Light Source 2:  $Y_2 = 20\text{lm}; x_2 = 0.4; y_2 = 0.5$  (blue)

Light Source Sum:  $Y = 30\text{lm}; x = 0.23; y = 0.33$  (bluish white)

**REMARK:**

Twice as much yellow flux than blue flux but it still appears bluish, because the blue is "stronger" than yellow ( $m_1 > m_2$ , in this particular case).



# Colorimetric quantities

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

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

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

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

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

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

$$x + y + z = 1$$

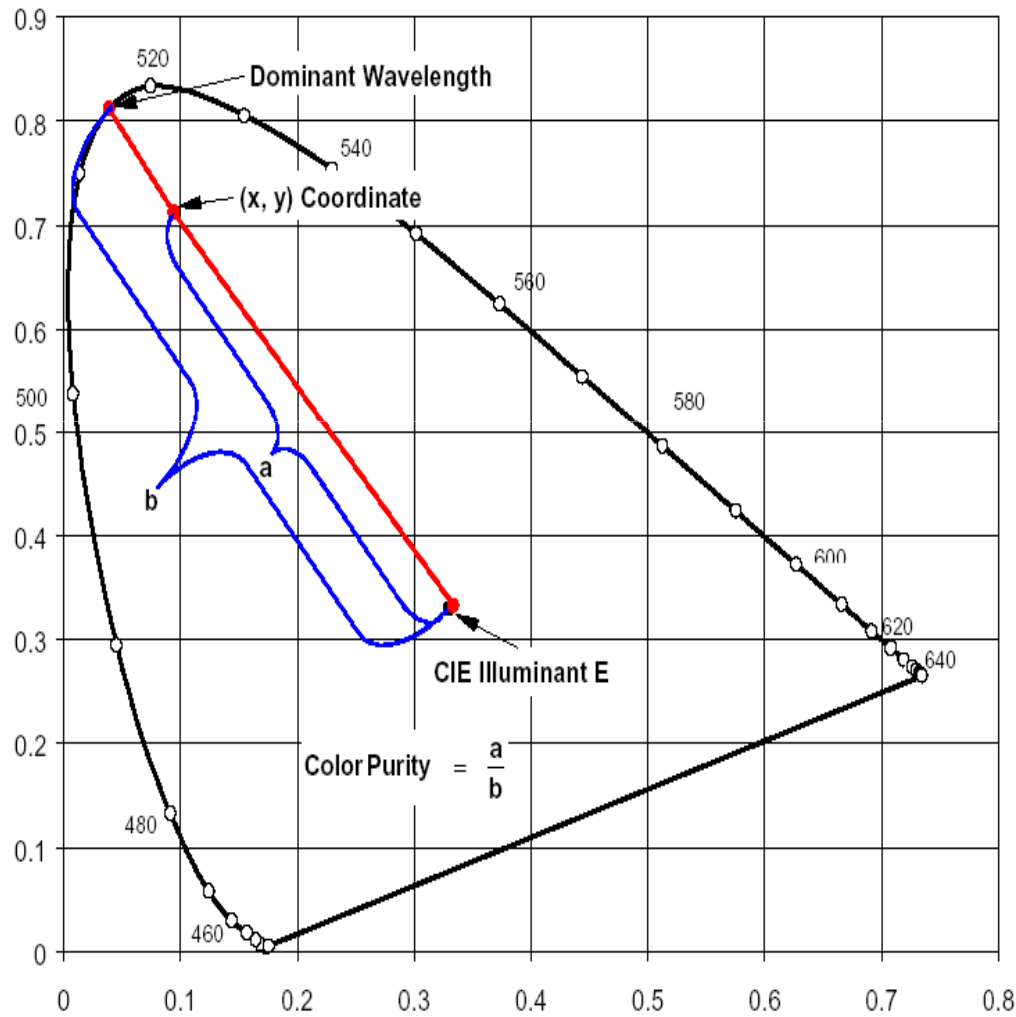
$P(\lambda)$  is the radiated spectrum of the light source  
(i.e. the spectral intensity of the source)

$x(\lambda)$ ,  $y(\lambda)$  and  $z(\lambda)$  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)

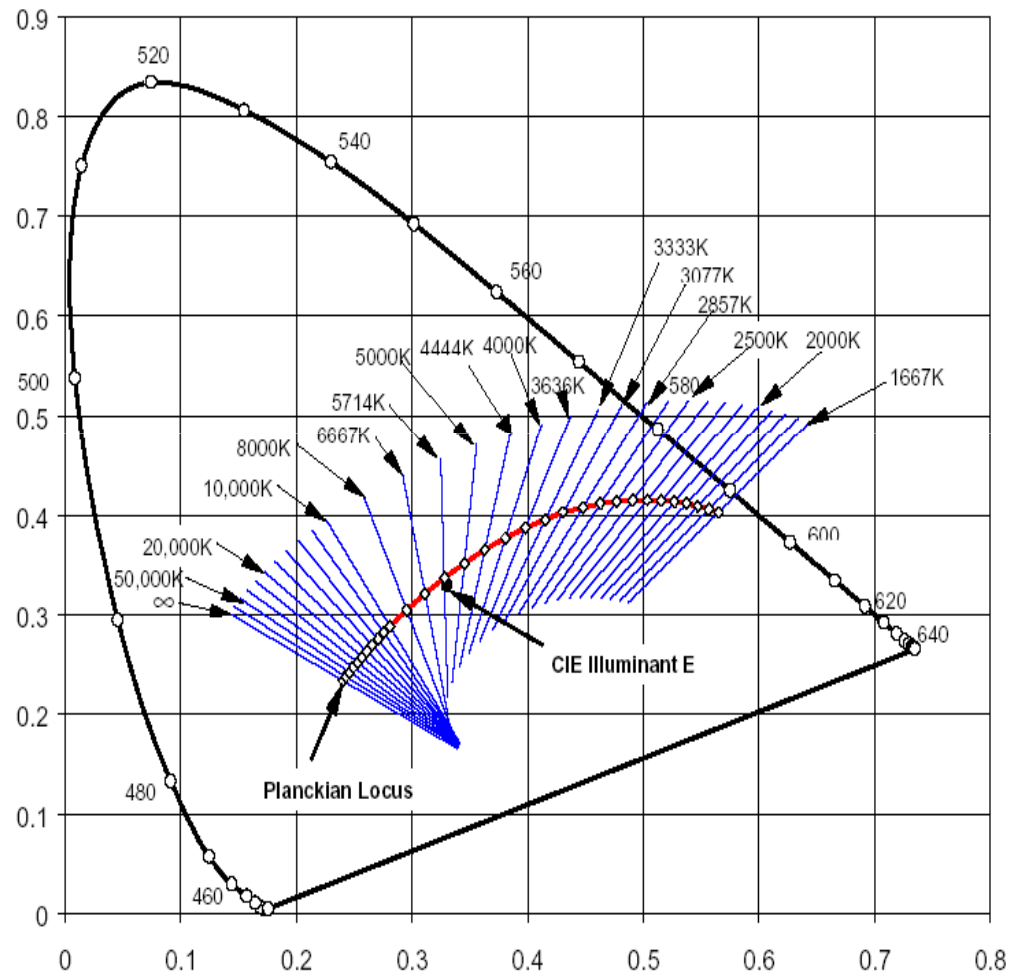
$x$ ,  $y$  and  $z$  are the color coordinates  
( $x$  and  $y$  are the coordinates in the CIE-Diagram)

# Color Purity



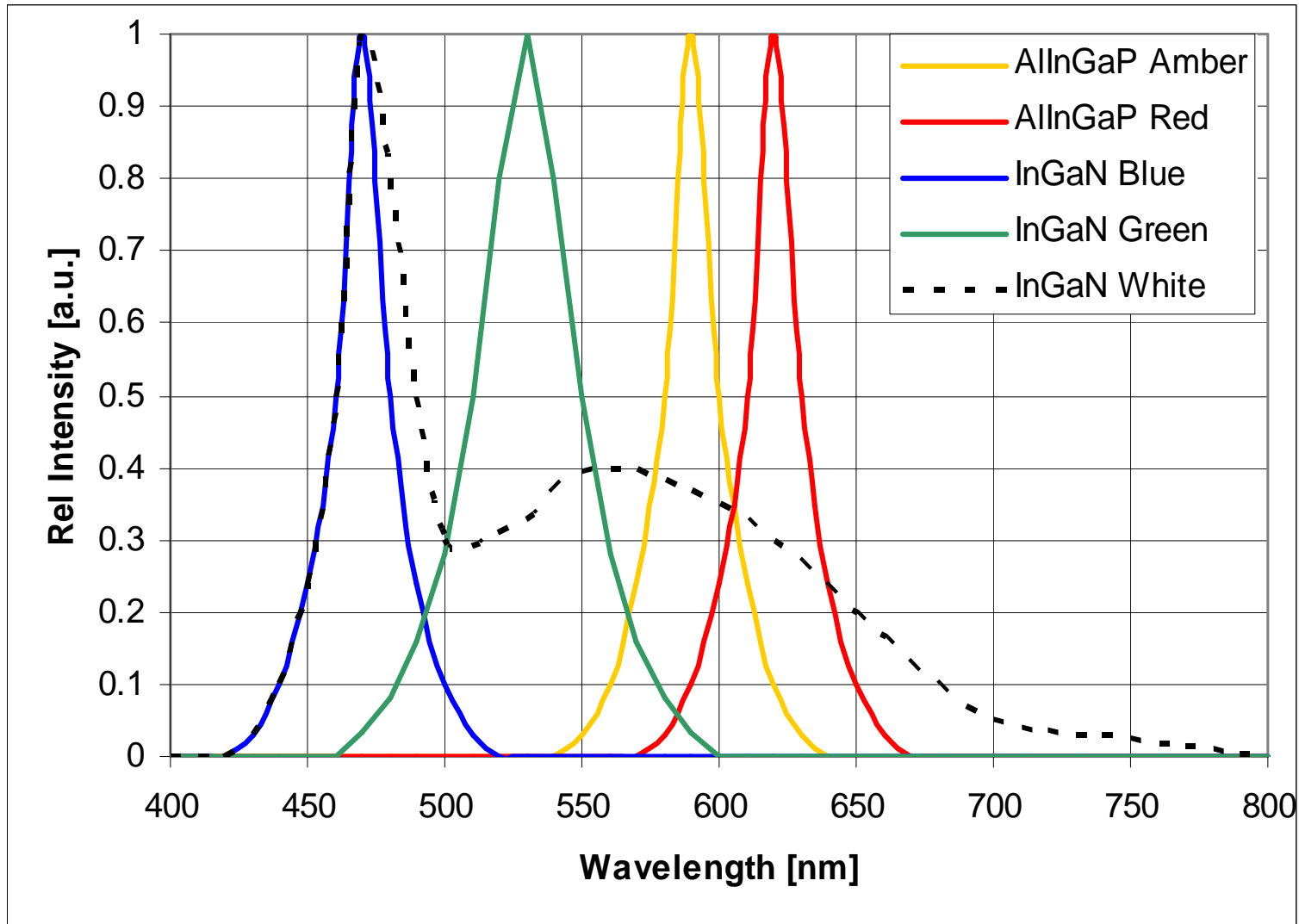
- Color Purity defines “how far away” a color is from it’s corresponding pure color
- Reference is Illuminant E(0.333,0.333)
- Color Purity= a/b

# Correlated Color Temperature

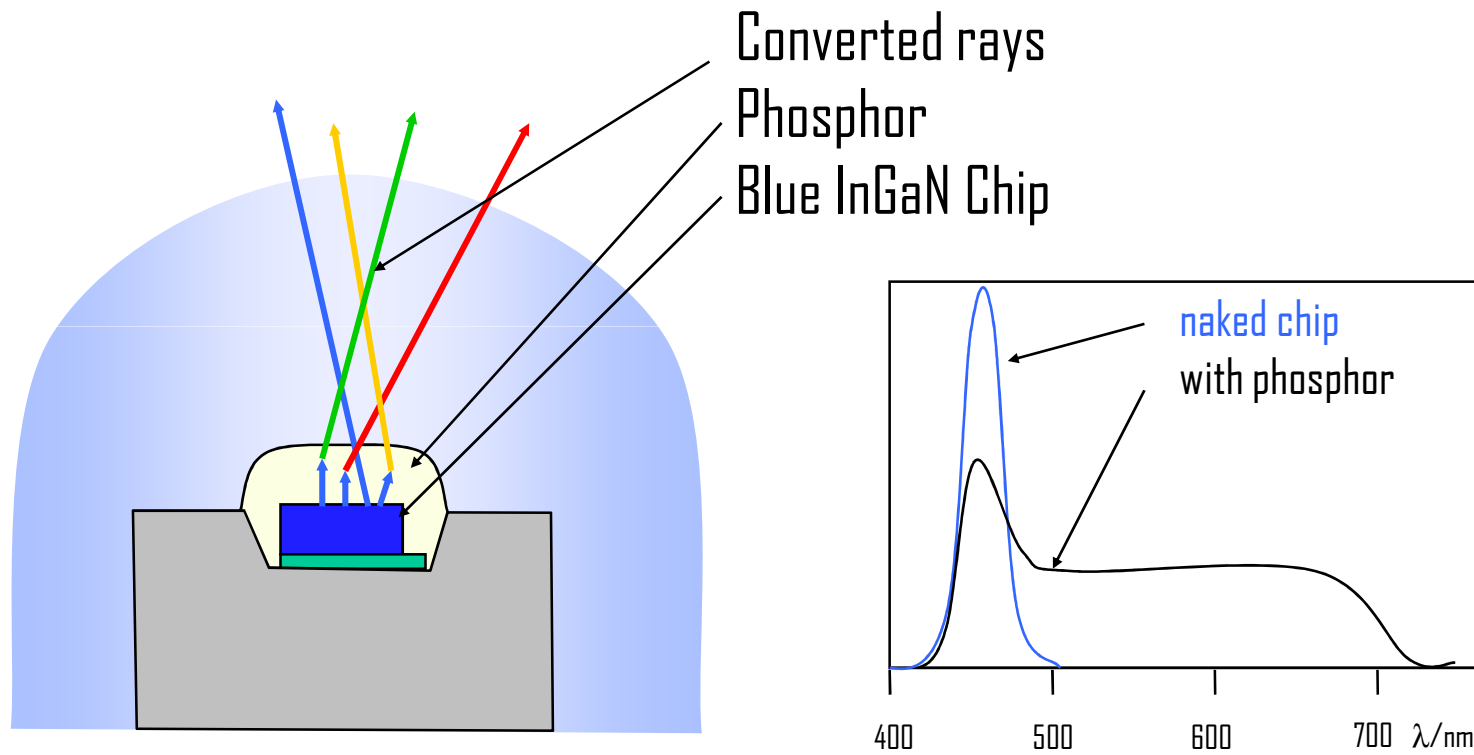


- Correlated Color Temperature (CCT) is the temperature of a black body source most similar in color to a source in question
- Only applicable for sources close to the black body curve (white light)

# Typical LED Spectra



# InGaN white LED Structure



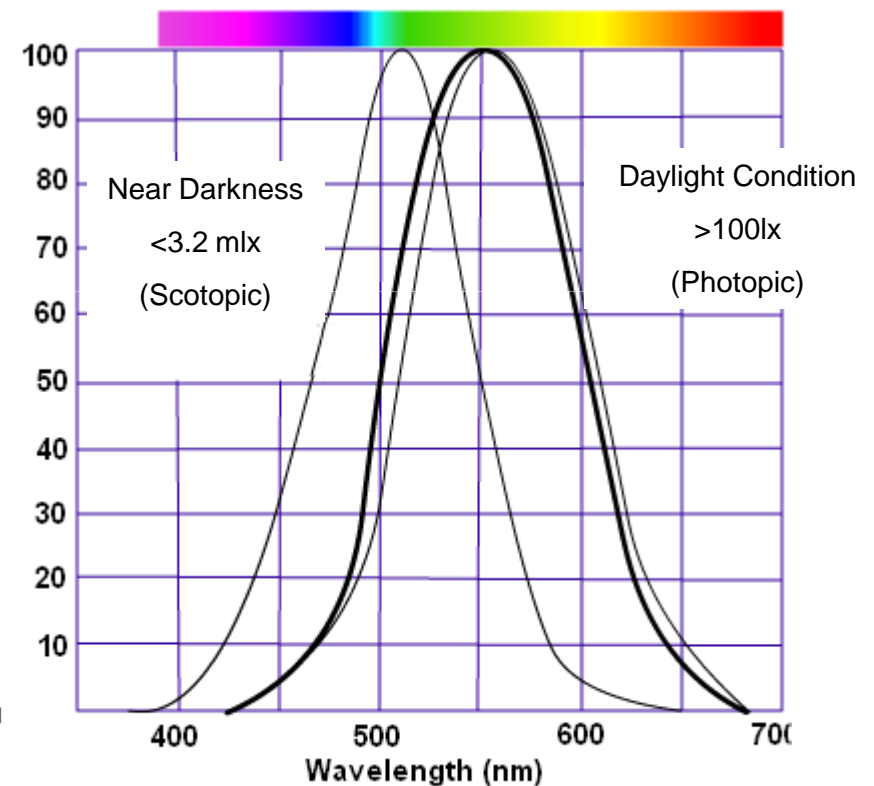
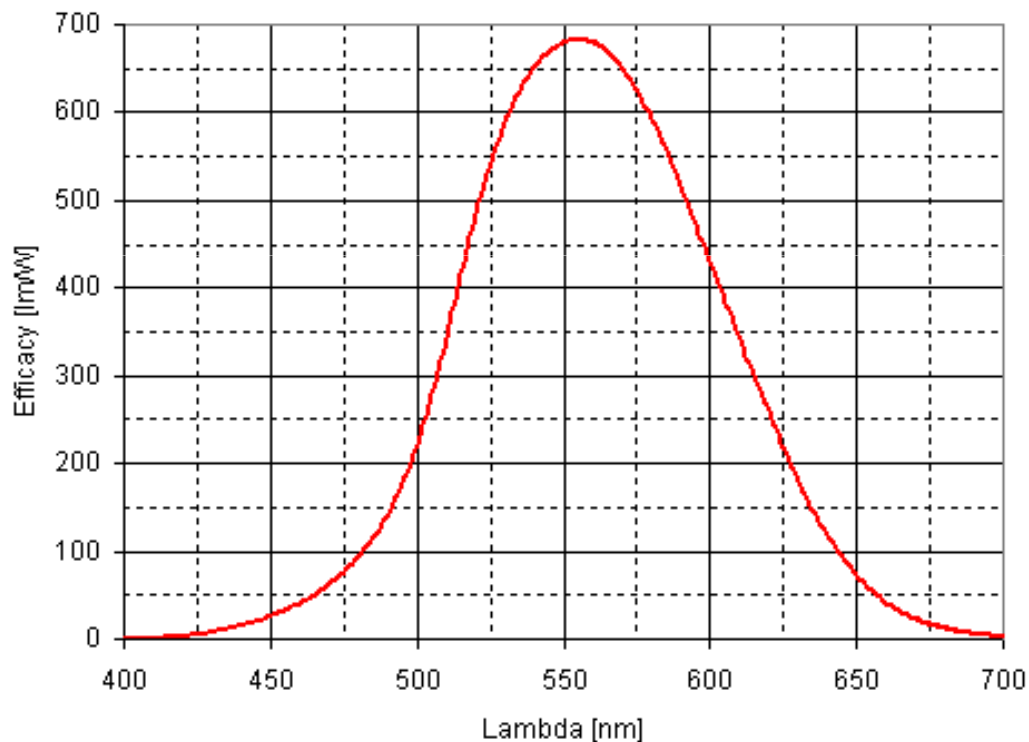
# The Human Eye Response

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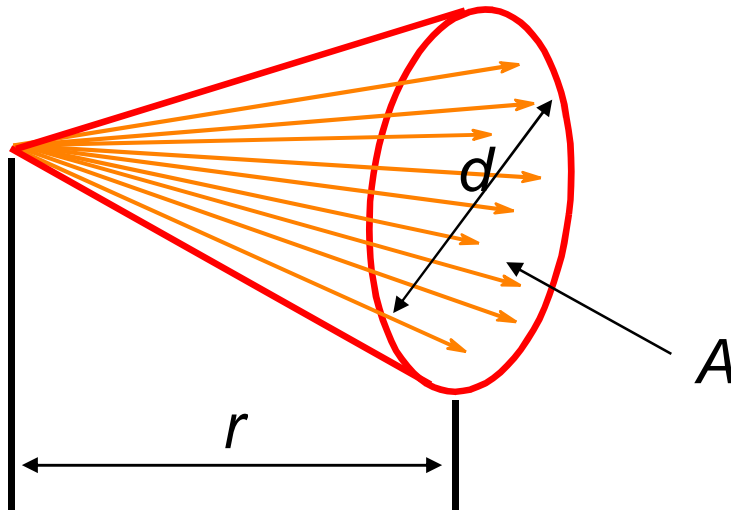
- All radiation which can be seen with the eye is considered light (approx. 400nm to 750nm)
  - **Radiation** is measured in radiometric units, and
  - **Light** is measured in photometric units.
- The sensitivity of the eye is dependant on the wavelength of the light (e.g. the eye is 10,000 times more 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



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 $\Omega$



Definitions:

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

for  $d \ll r$ :

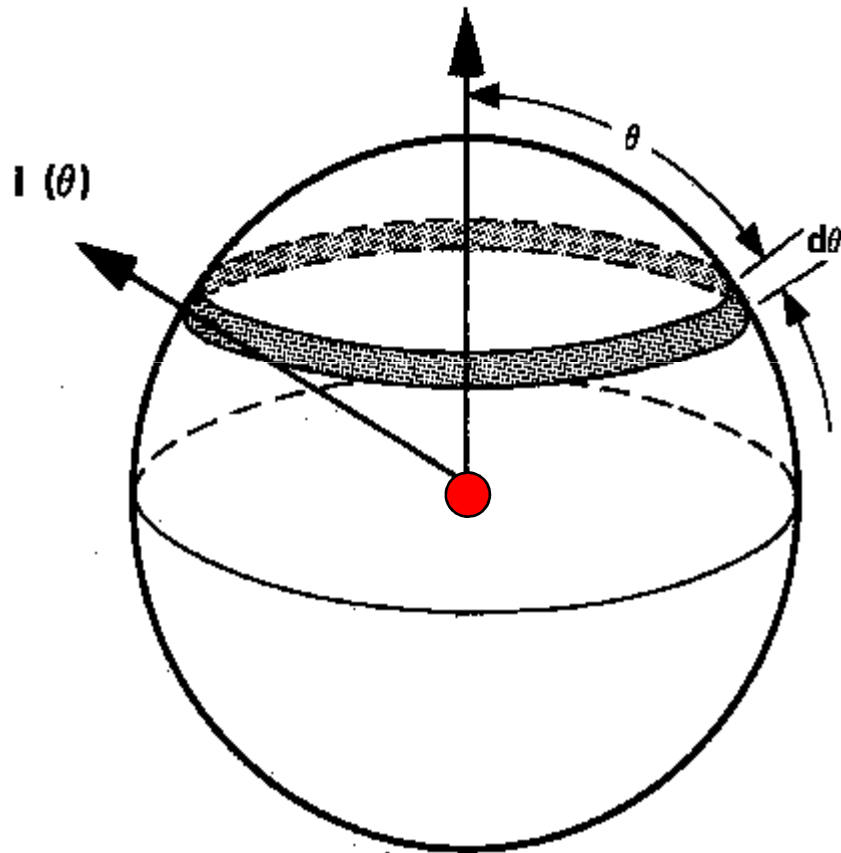
$$\Omega = \frac{A}{r^2} = \frac{\pi d^2}{4r^2}$$

Radiometric Intensity:  $I_v$  [W/sr]

Photometric Intensity:  $I$  [lm/sr] or [cd], Candela

Solid Angle Units:  $\Omega$  [sr], Steradian

# Conversion from Intensity to flux



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

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

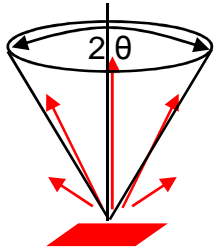
Rewrite in integral Form :

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

Total Flux for rotational Symmetry :

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

# Lambertian Emitter

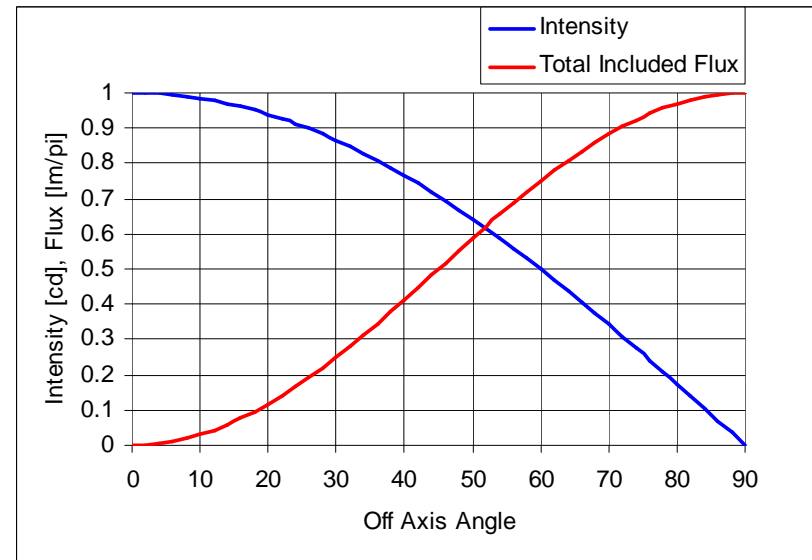


Typical radiation pattern of a flat surface :  
(i.e. LED chip top surface)

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

Total flux in a cone with an opening angle  $2\theta$ :

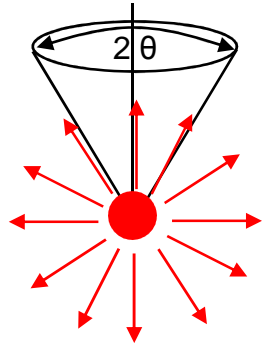
$$\begin{aligned} \Phi &= 2\pi \int_0^\theta I(\theta') \sin(\theta') d\theta' \\ &= 2\pi \int_0^\theta I_0 \cos(\theta') \sin(\theta') d\theta' \\ &= \pi \sin^2(\theta) I_0 \end{aligned}$$



The total flux of a Lambertian source of 1 cd on axis is  $\pi$  lm!

To collect for example 90% of the Flux of a Lambertian source, the optics must capture a cone  $\pm 72$  deg off axis angle

# Uniform Emitter

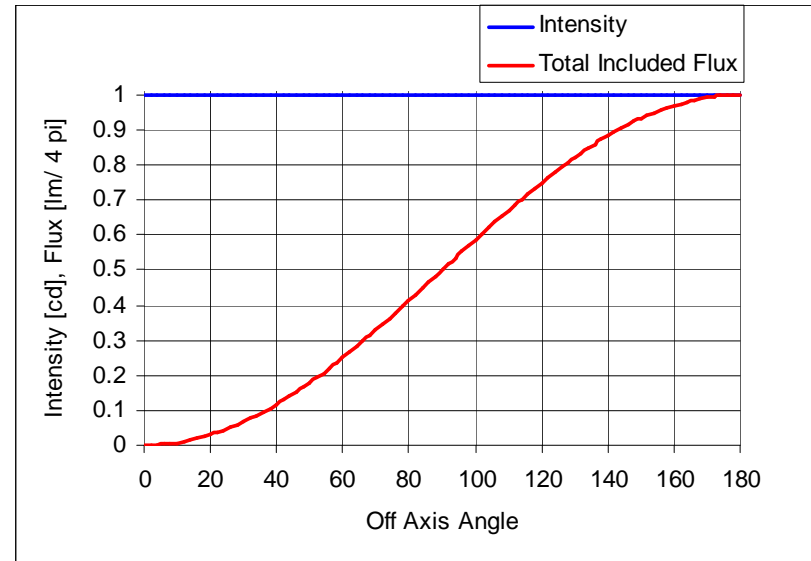


Typical radiation pattern of a spherical surface (i.e. the sun), or of, as a rough approximation, an incandescent filament.

$$I(\theta) = I_0 = \text{const}$$

Total flux in a cone with an opening angle  $2\theta$ :

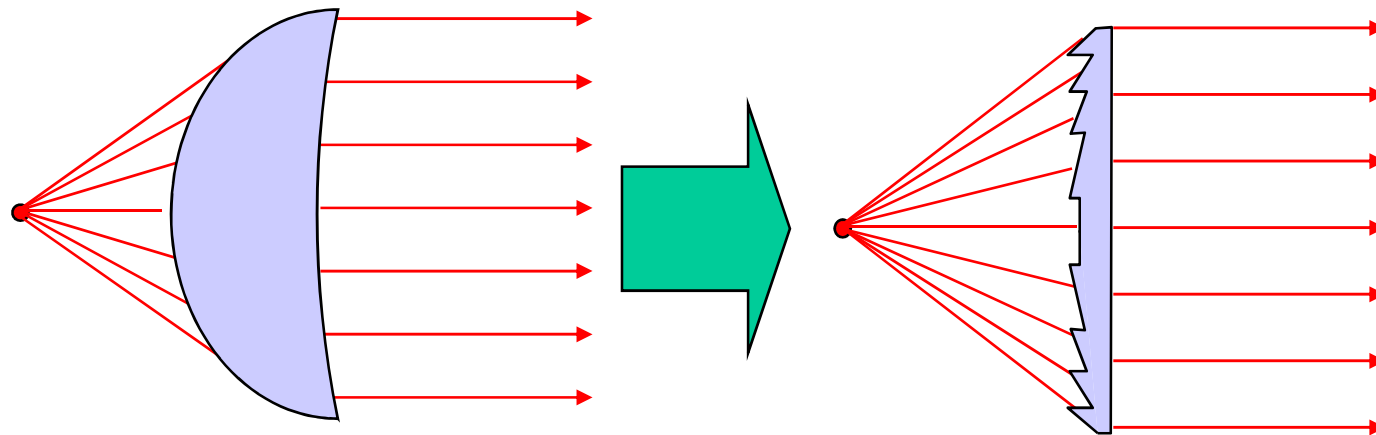
$$\begin{aligned} \Phi &= 2\pi \int_0^\theta (I(\theta') \sin(\theta')) d\theta' \\ &= 2\pi \cdot I_0 \int_0^\theta \sin(\theta') d\theta' \\ &= 2\pi \cdot I_0 (1 - \cos(\theta)) \end{aligned}$$



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

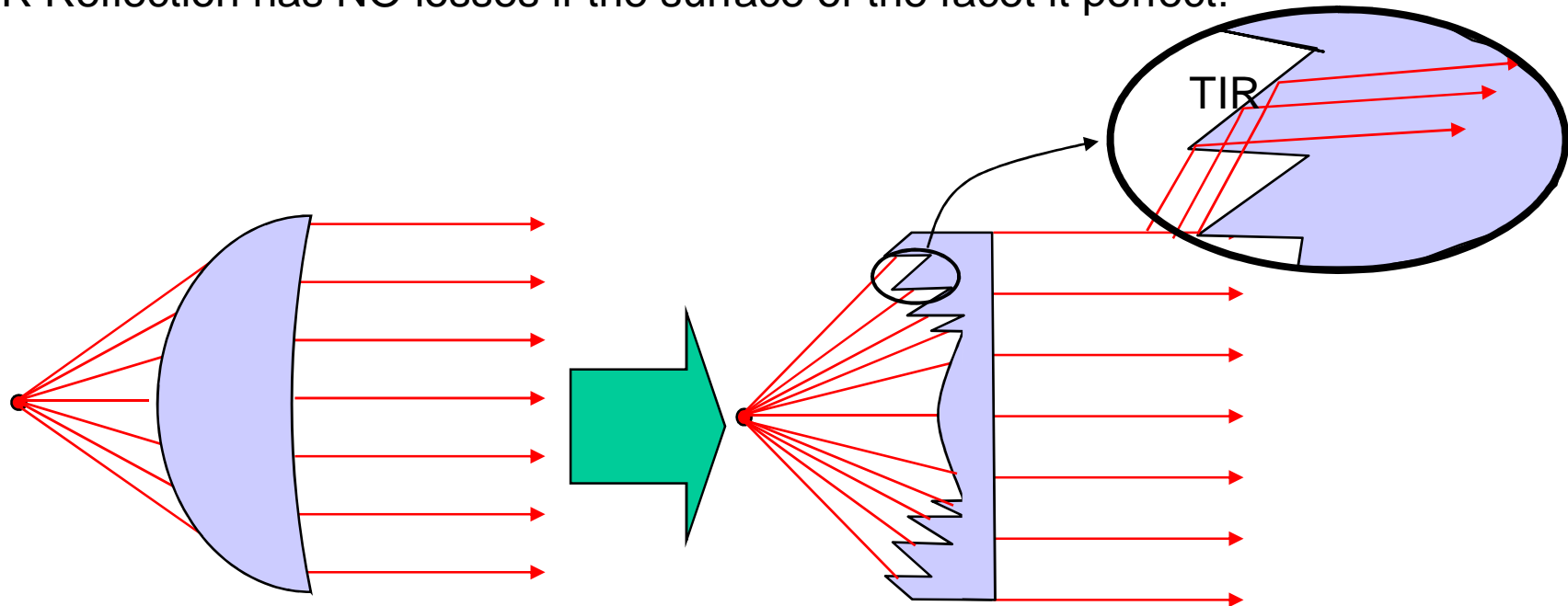


Conventional lens

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, not so efficient for small angles
- TIR Reflection has NO losses if the surface of the facet is perfect!



Conventional lens

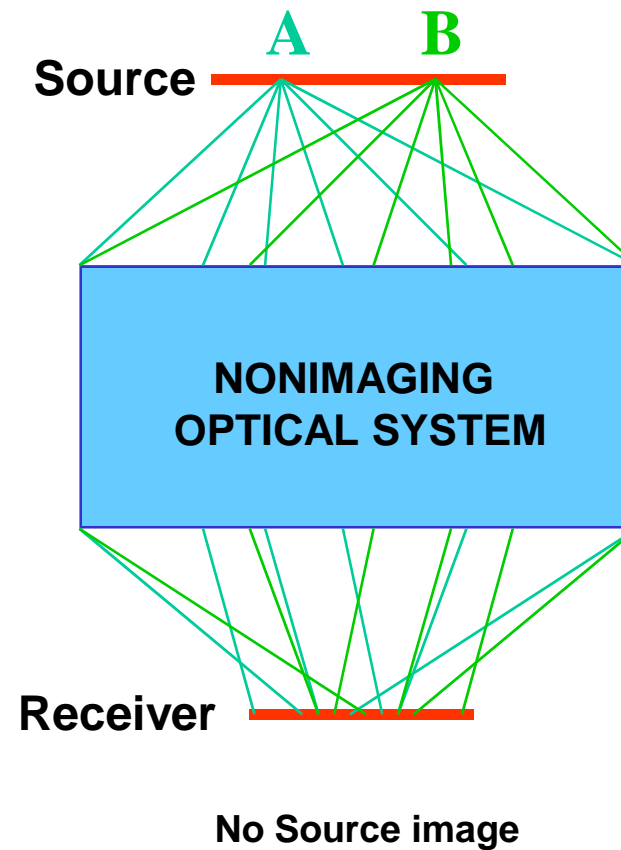
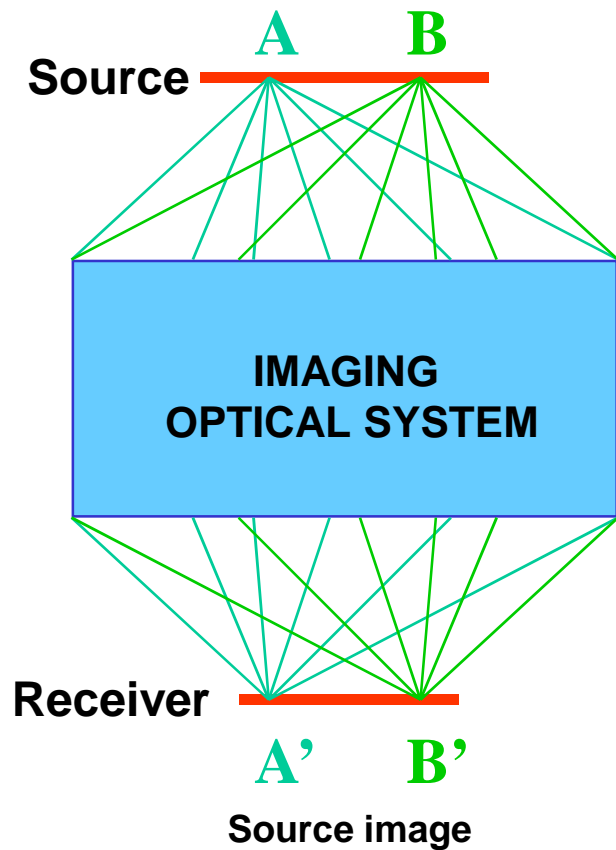
TIR lens

# Nonimaging Optics (NIO)

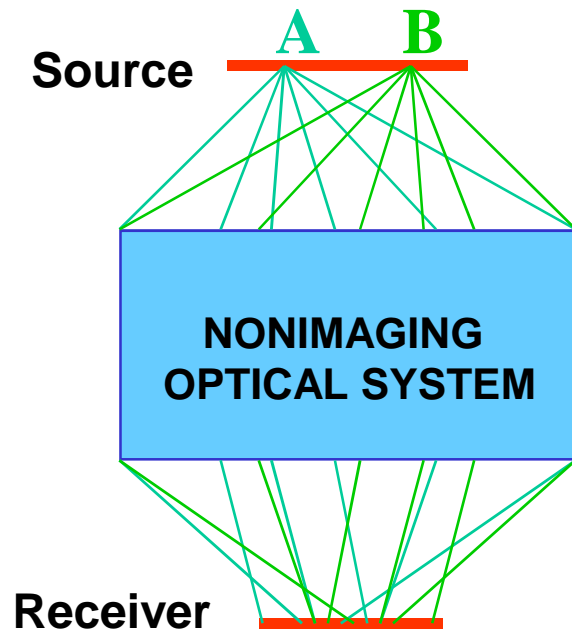
**NIO**



**optimum transfer of  
luminous power**



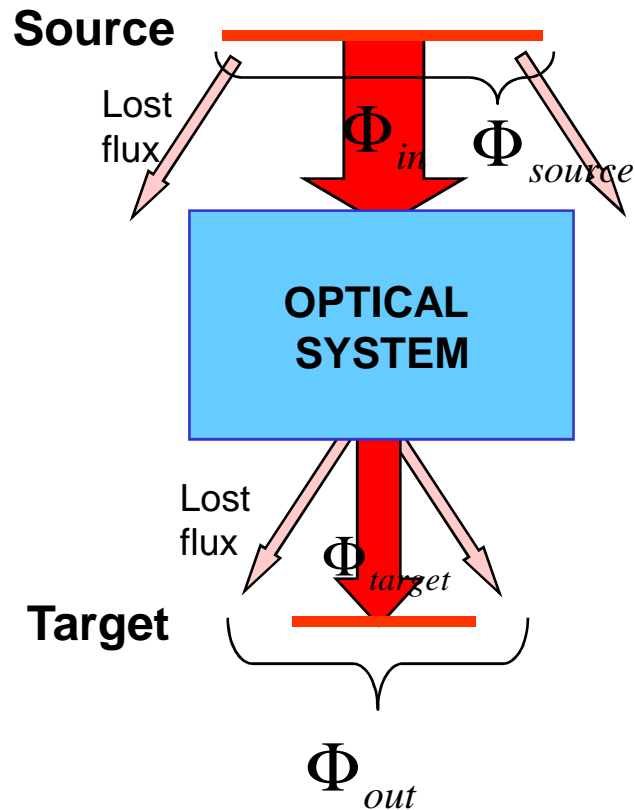
# NIO Design Rules



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]:

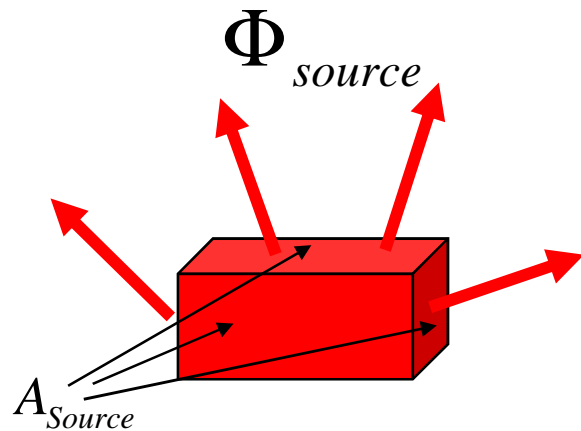
$$E = \frac{d\Phi}{dA}$$

“Flux emitted by a surface element”

## Average Source Illuminance:

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

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



“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

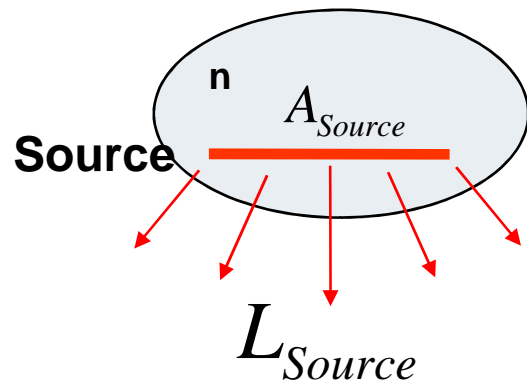
# Luminance

Luminance [ $\text{cd}/\text{m}^2$ ]:

“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

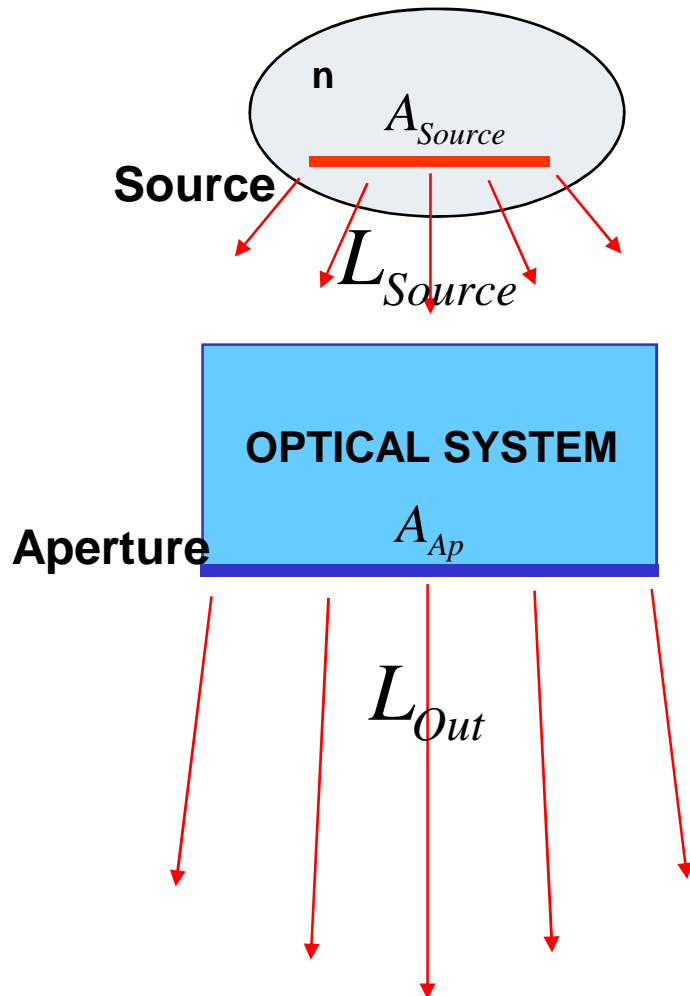
Typical values for a filament bulb (n=1): 5-20  $\text{cd}/\text{mm}^2$

Good bulb (automotive halogen): approx. 25  $\text{cd}/\text{mm}^2$

White LEDs: up to: 100  $\text{cd}/\text{mm}^2$ , constantly improving

Sun: 1500  $\text{cd}/\text{mm}^2$

# Luminance Conservation



## Luminance Conservation:

$$L_{out} = t \cdot L_{Source} \quad \text{“Conservation of brightness”}$$

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<sup>2</sup>,  $t=0.7$ :  $A_{ap} > 680 \text{ mm}^2$

\*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

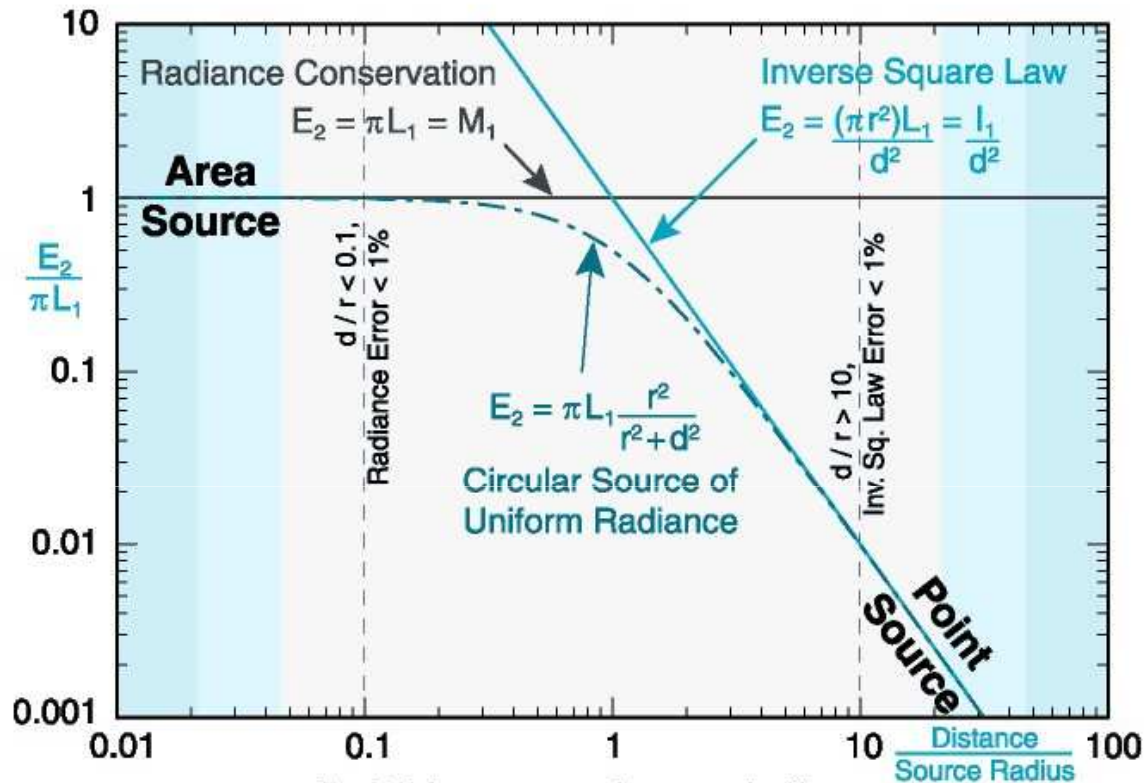


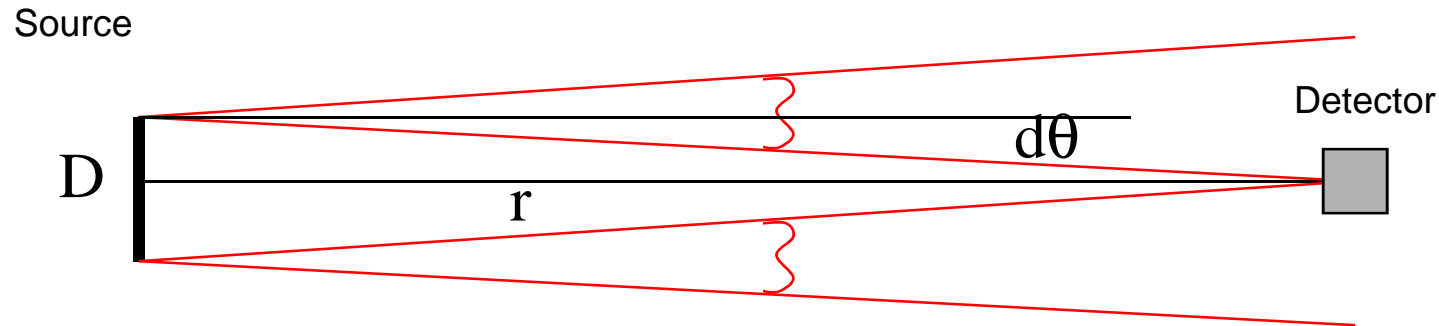
Fig. 6.2 Inverse square law approximation error.

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  $L_1$ . To the far field intensity is  $\pi r^2 L_1$  and the signal at the detector  $E_2 = I_1 / d^2$

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  $d/r=0.1 \dots 10$ .

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  $d\theta$ , the detector has to be at a distance of at least:  $R > D / (2 \tan(d\theta))$ . This insures that light emitted with  $d\theta$  from any point of the source (the extreme edges) hits the detector

Examples:

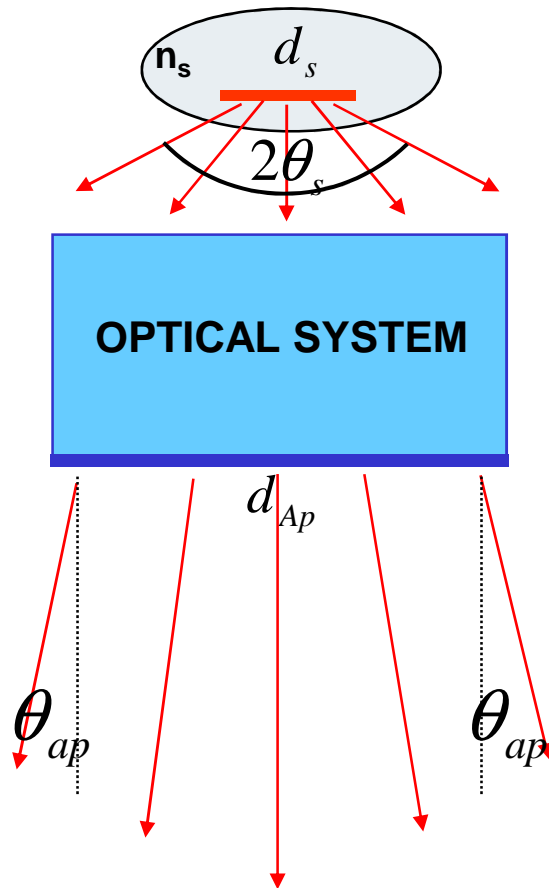
$D = 50 \text{ mm}$ ,  $d\theta = 1 \text{ deg} \Rightarrow r > 1.4 \text{ m}$

$D = 50 \text{ mm}$ ,  $d\theta = 0.2 \text{ deg} \Rightarrow r > 7 \text{ m}$

$D = 100 \text{ mm}$ ,  $d\theta = 0.1 \text{ deg} \Rightarrow r > 28 \text{ m}$  (automotive headlamp)

# Etendue Conservation, Simplified

## Source



## 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.

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

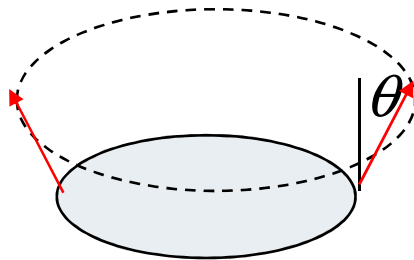
Formula can be used in the horizontal and vertical direction independently.

Example: Desired exit angle  $\theta_{ap}=5^\circ$  (half angle!),  $d_s=1$  mm,  $n_s=1.5$ ,  $n_{ap}=1$ ,  $\theta_s=90^\circ$  (collect full LED flux) => minimum aperture width:  $d_{ap}=17$  mm

A smaller aperture can yield the same collimation angle  $\theta_{ap}$ - if the collection angle  $\theta_s$  is reduced. =>

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

# Etendue 3D, simplified



**Source, A**

Etendue in 3 Dimensions,  
rotational symmetric emission

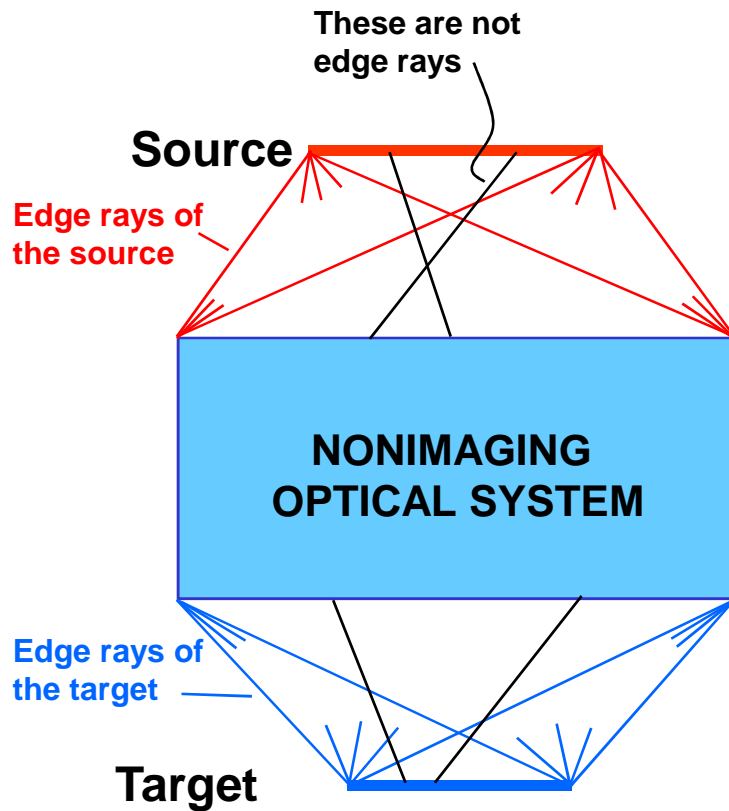
$$E = \pi \cdot n^2 \cdot \sin^2(\theta) \cdot A$$

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.

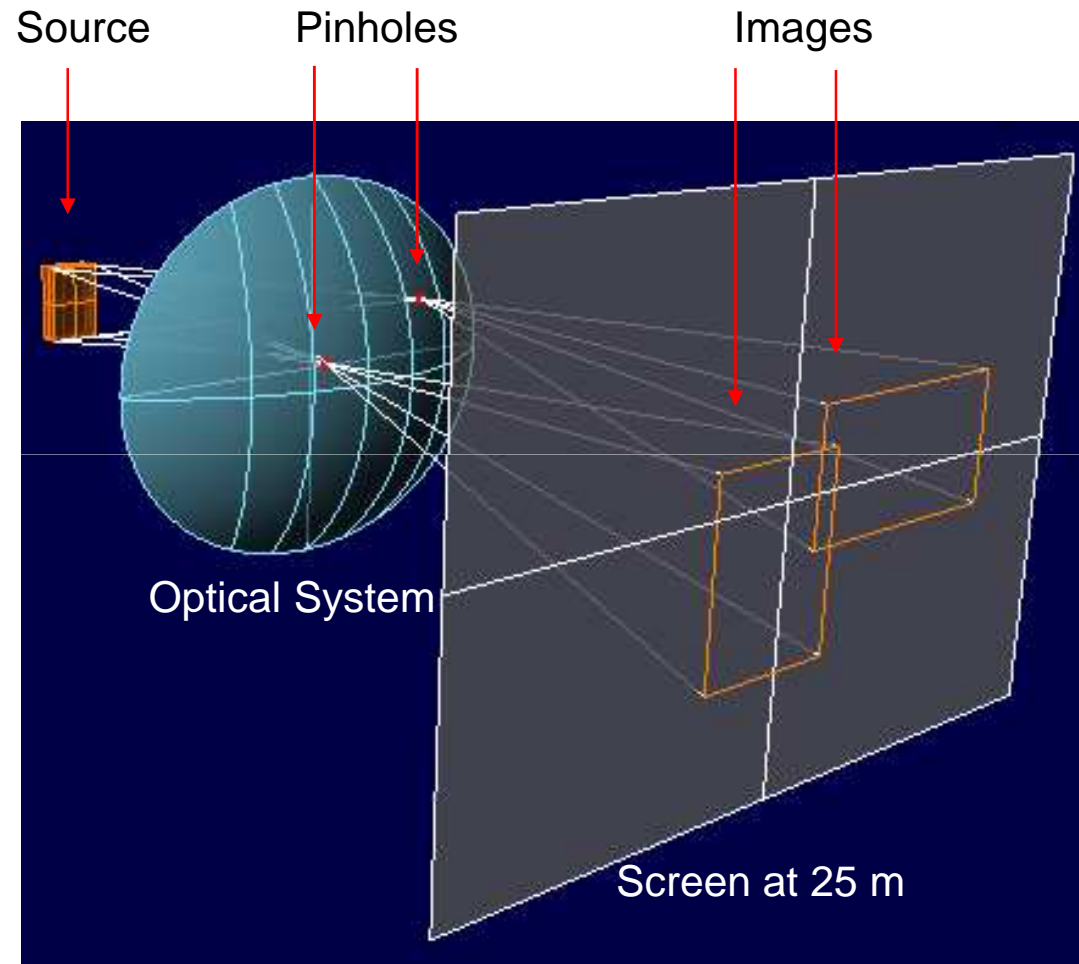
In simpler words:

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

---



- ◆ 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

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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

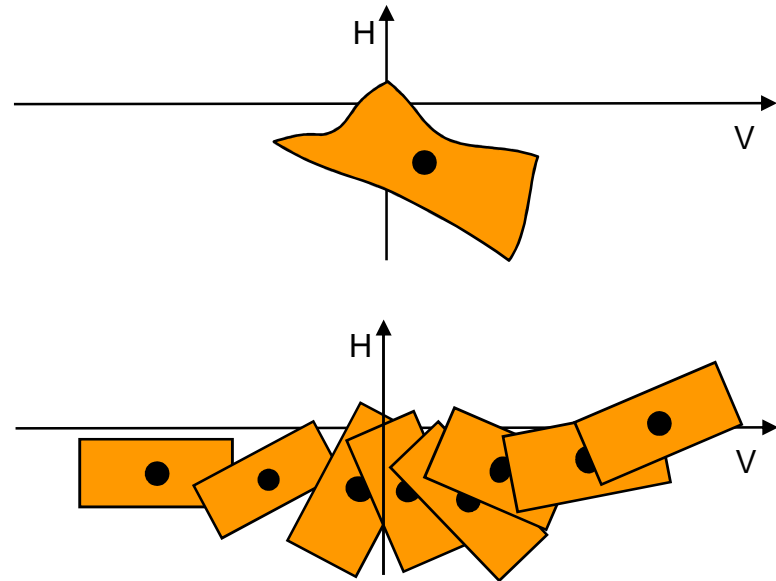
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- Creates **one** free-from surface (= reflective or refractive surface, others can be “chosen”)
- Can be solved either by iterative procedures or by solving non-linear differential equation
- Allows to produce a desired radiation pattern for a **Point 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”

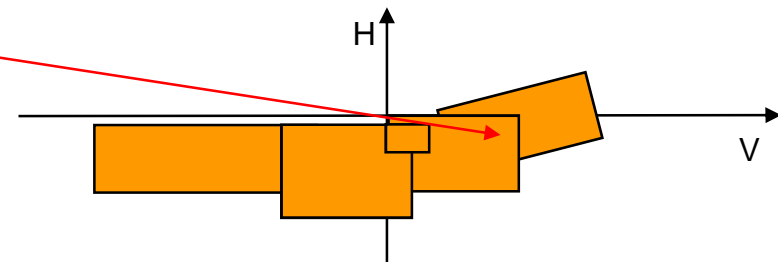
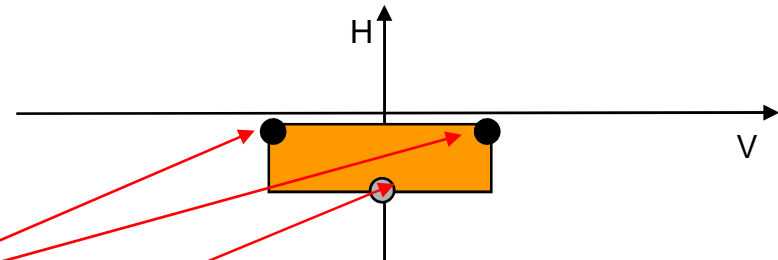
# Conventional Free Form Design Methods

- Design controls only the position of **one** point of the source image (center, edge or corner) but not its 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 esthetics



# Comparison Conventional/ SMS

	<b>Conventional</b>	<b>SMS</b>
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 distinguishing 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.

