Photometry for Traffic Engineers...

Workshop presented at the annual meeting of the Transportation Research Board in January 2000

by

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Many figures borrowed from:
Ryer, A. Light Measurement Handbook. http://www.intl-light.com/handbook/
(An excellent and practical resource!!!)

Basic Light Measurement

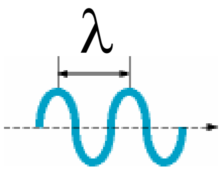
- Visible Electromagnetic Radiation (Light)
- Radiometric to Photometric Conversion
- Luminous Flux (Lumens)
- Luminous Intensity (Candela)
- Illuminance (Lux)
- Luminance (cd/m^2)

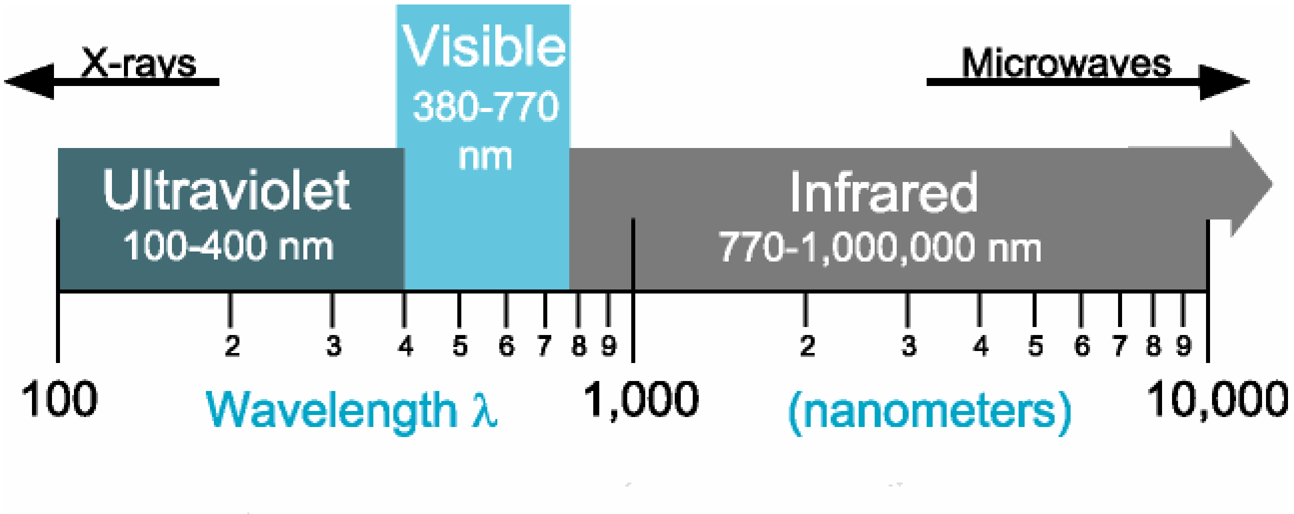
Taxonomy of Photometric Units

Luminous Flux	Lumen	Total “effective” output of a lamp
Luminous Intensity	Candela	Light density through space • Vehicle headlamps • Traffic signal lamps/lenses
Illuminance	Lux	Light density falling upon a surface • Roadway illumination • Highway sign illumination
Luminance	Candela/m^2	Brightness of extended source/surface • Highway sign brightness/contrast •Proxy for “retroreflectivity”

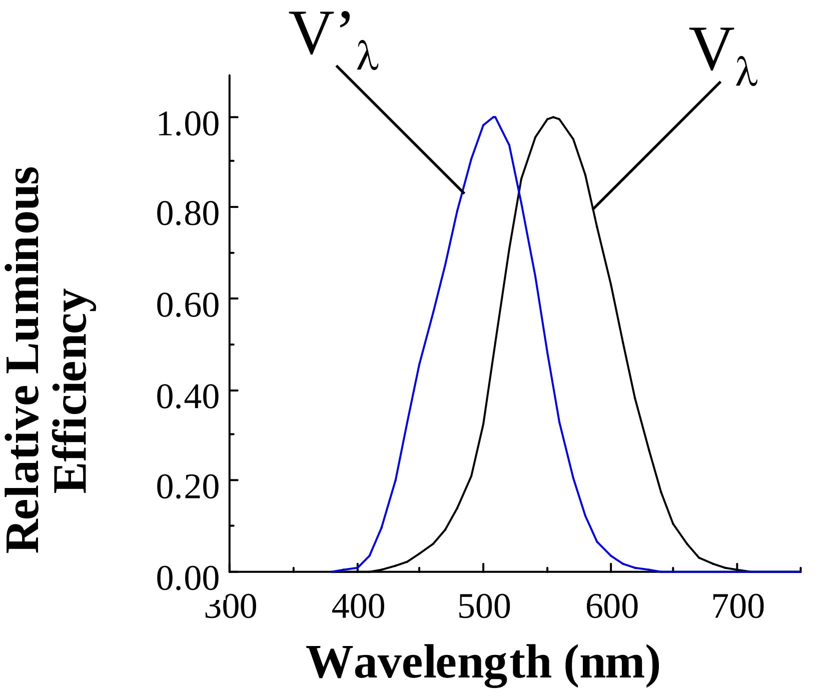
Light Energy

- Light is visible electromagnetic radiation
- Magnitude measured in Watts (1/746 H.P.)
- Wavelength (λ): 380 to 730 nm
- Frequency: 789 down to 384 THz



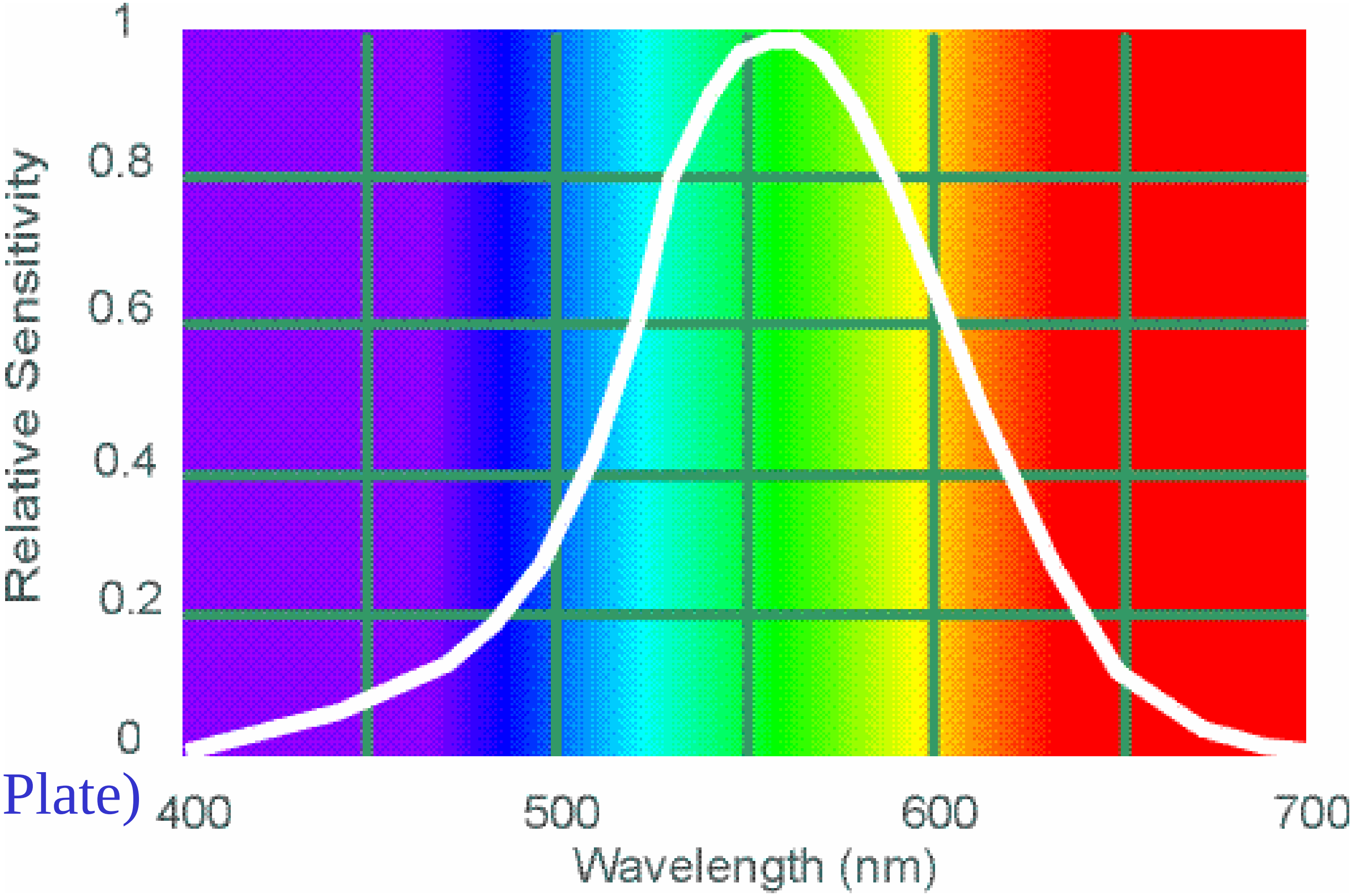


CIE Spectral Luminosity Function



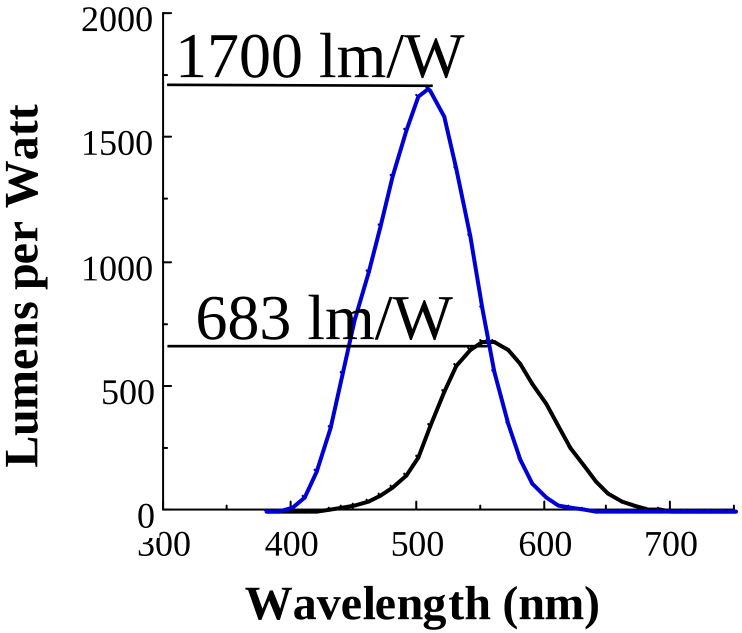
- The human eye is more sensitive to some visible wavelengths than others
- Measurements of light must take these effects into account
- CIE V_λ curve corrects for the differences across wavelengths

Commission Internationale de l'Eclairage (CIE) V_λ



(Color Plate)

Radiometric to Photometric Conversion via CIE V_λ and V'_λ



Scotopic (V'_λ)

Dark Adapted

Peak λ = 507 nm

K_m = 1700 lm/W

2.5 X Sensitivity

Photopic (V_λ)

Light Adapted

Peak λ = 555 nm

K_m = 683 lm/W

Luminous Flux
(The Lumen)

Luminous Flux

- Luminous Flux is the photometrically (V_λ) corrected equivalent of the Watt
- 1 Lumen = 1/683 Watts at 555 nm (peak V_λ)
- Luminous Flux in lumens is calculated as:

$$683 \int_{380}^{730} \Phi_{e,\lambda} \; V(\lambda) \; d\lambda$$

Luminous Flux Equation Revealed

Lumens per Watt Conversion Factor for CIE V_λ Curve

Radiant Energy in Watts

Wavelength Sampling Increment

$$\text{Lumens} = 683 \int_{380}^{730} \Phi_{e,\lambda} \; V(\lambda) \; d\lambda$$

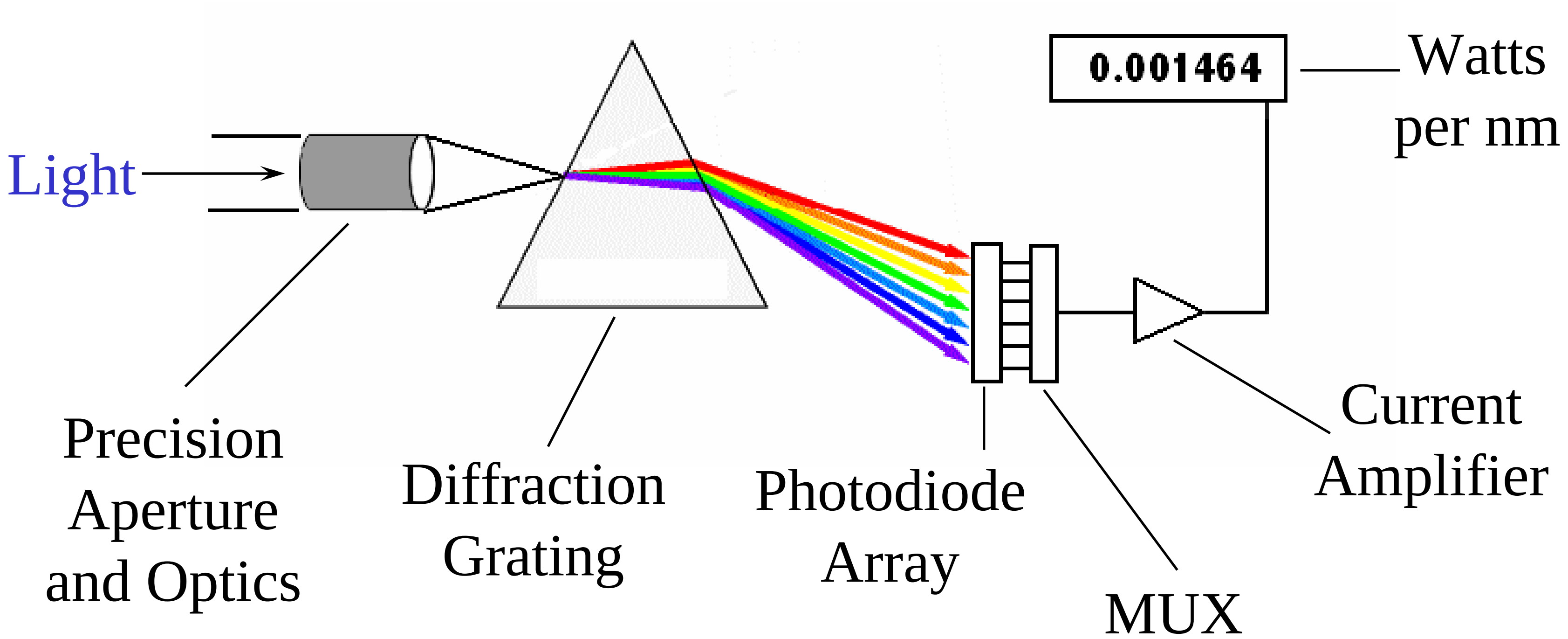
Integrate over Visible Spectrum

CIE Spectral Luminosity Function

Step-by-Step Calculation of Luminous Flux

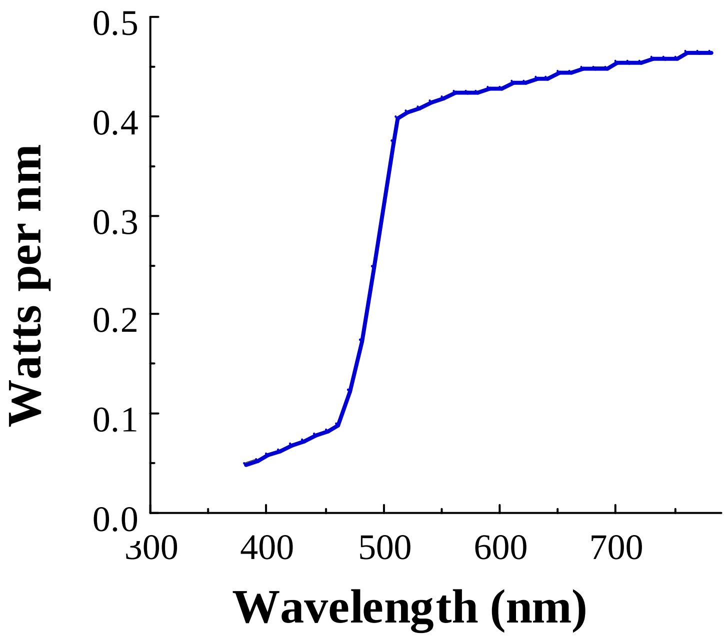
- Measure radiant energy (Watts) from light source at each λ across the visible spectrum (380 - 730 nm)
- Convert Watts to Lumens via the V_{λ} curve and the photopic maximum luminous efficiency constant (683 lm/W at 555 nm)
- Integrate Lumens across visible spectrum

Step 1.
Measure Radiant Energy across λ using a Spectroradiometer



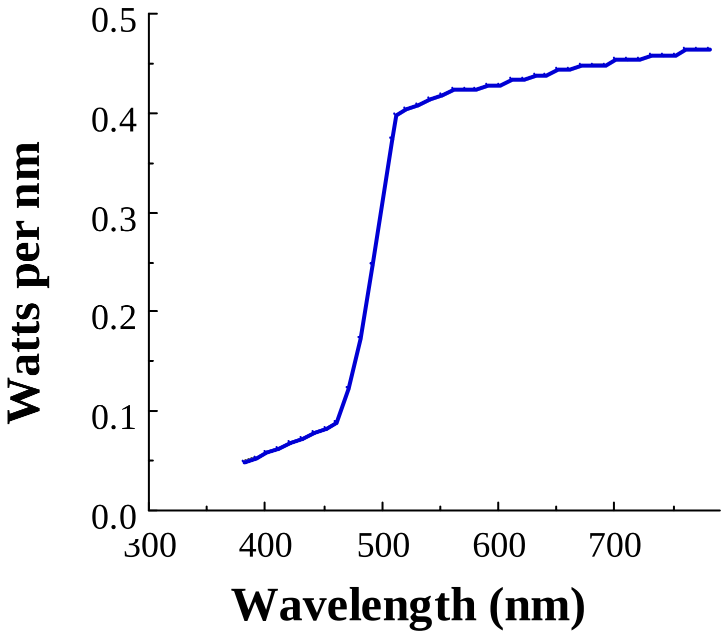
(See next slide for sample data)

Sample Data from Spectroradiometer



Radiant Flux (Watts) measured every 10 nm from 380-730 nm

Step 2.
Convert Watts to Lumens



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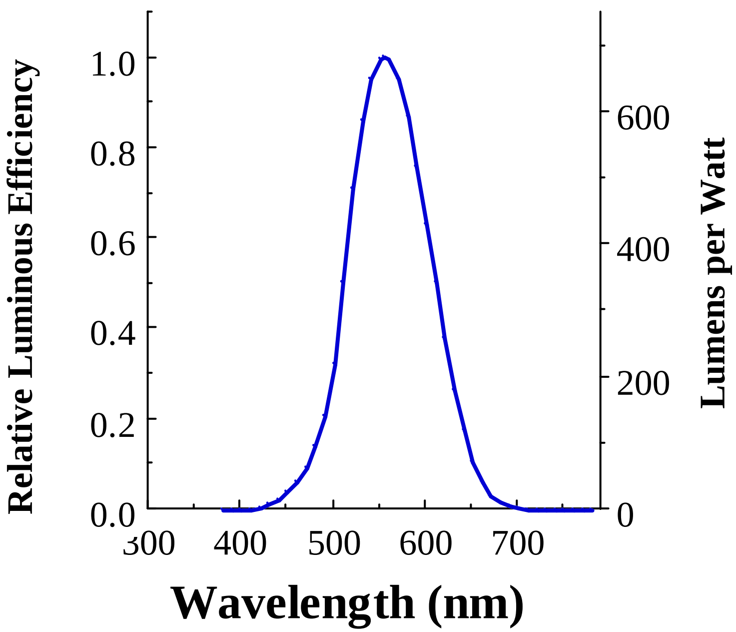

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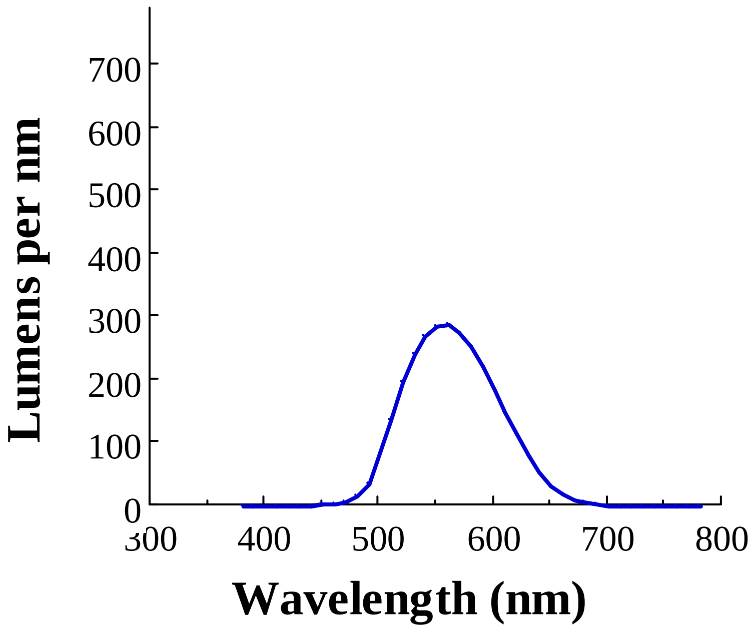
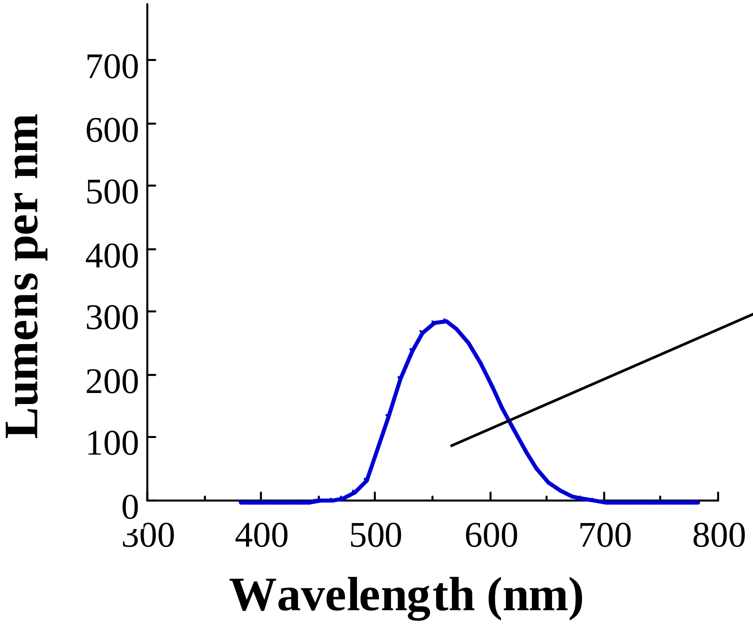
(See next slide for results)

Results of V_λ Conversion



Step 3.
Integrate Lumens from 380-730 nm



Integration across the visible spectrm yields a Luminous Flux measurement of 2890 Lumens

Luminous Flux Equation Revisited

Lumens per Watt
Conversion Factor for
CIE V_λ Curve

Radiant Energy
in Watts

Wavelength
Sampling
Increment

$$\text{Lumens} = 683 \int_{380}^{730} \Phi_{e,\lambda} \, V(\lambda) \, d\lambda$$

Integrate over
Visible Spectrum

CIE
Spectral Luminosity
Function

Luminous Intensity
(The Candela)

Luminous Intensity

Luminous Intensity refers to the amount of luminous flux emitted into a solid angle of space in a specified direction (since many sources are not isotropic)

The SI unit of Luminous Intensity is the candela

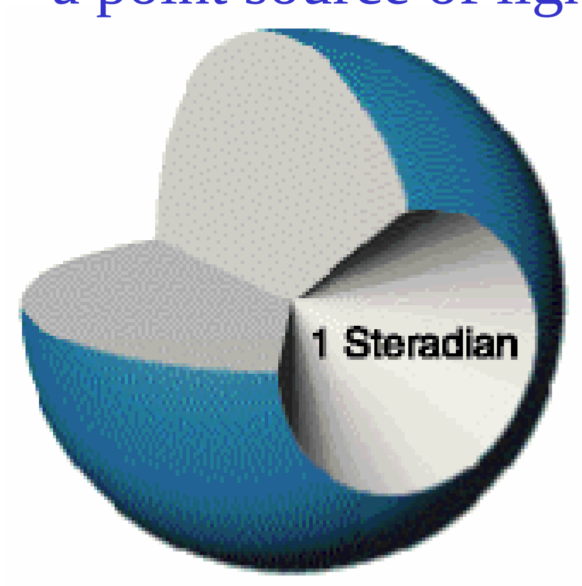
The candela is historically linked to “candle power” (ie., 1/683 W/sr at 555 nm)

$$1 \text{ candela} = \frac{1 \text{ lumen}}{\text{unit solid angle}}$$

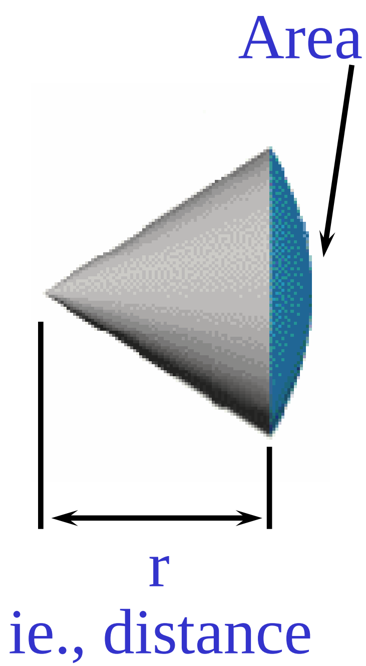
(unit solid angle ← steradian)

Solid Angles, Surfaces of Spheres and the Steradian

Imaginary Sphere Surrounding a point source of light



Sphere Area = $4\pi r^2$



Steradian (ω) = $\frac{\text{Area}}{r^2}$

1 m^2 subtends 1 sr at a distance of 1 m…since

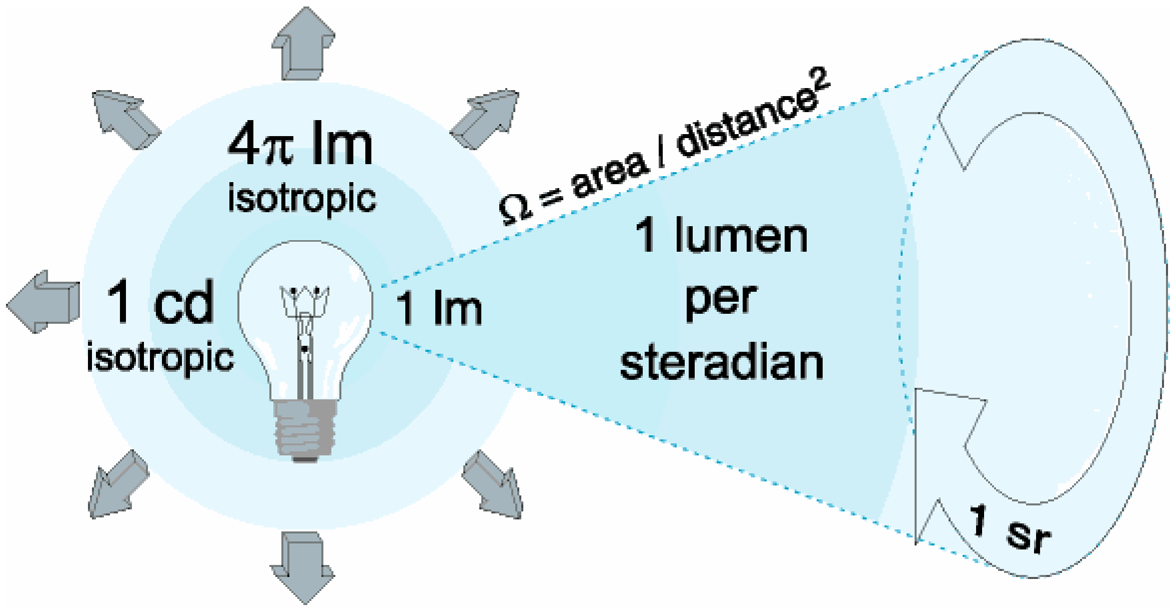
$$\omega = \frac{A}{r^2} = \frac{1\ m^2}{1\ m^2} = 1$$

Surface area of a sphere is subtended by 4π sr

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

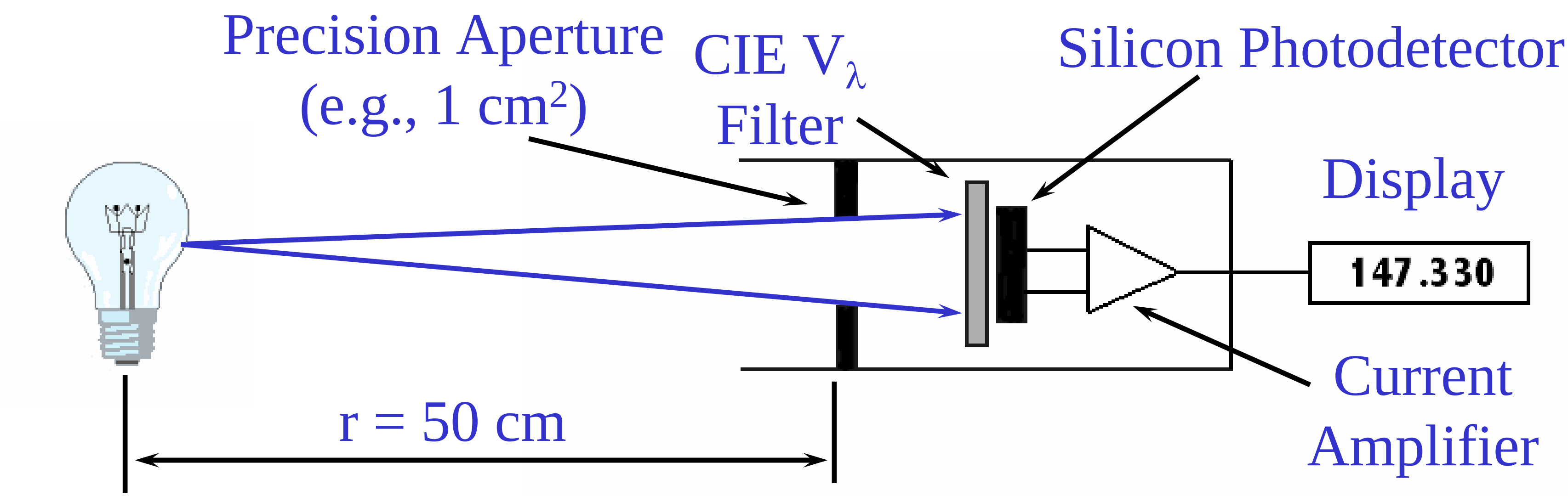
$4\pi = 12.56$

The Candela



An isotropic light source with a luminous intensity of 1 cd is emitting a total luminous flux of approximately 4π lumens (since an isotropic source emits light into a total volume of 4π sr)

Broadband Measurement of Luminous Intensity

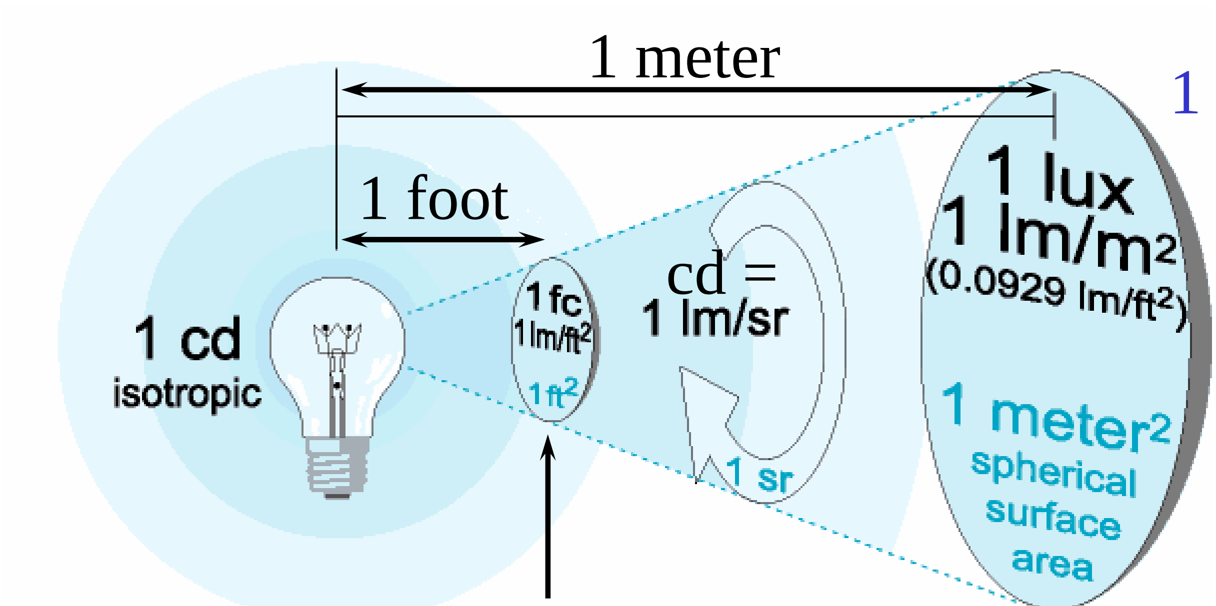


- Photometer aperture subtends 0.0004 sr at 50 cm distance
  ($\omega = \text{Area} / r^2 = 1\ \text{cm}^2 / 50\ \text{cm}^2 = 0.0004$ sr)
- Light energy in 0.0004 sr is filtered and converted to current
- Current is converted to lumens (per calibration constant)
- Lumens divided by 0.0004 sr = Candelas
  (e.g., 0.058932 lm / 0.0004 sr = 147.330 lm/sr (candelas))

Illuminance
(Lux)

Illuminance

The photometrically corrected light energy falling upon a given unit of surface area (e.g. lumens/m^2)



1 m^2 at distance of 1 m subtends 1 steradian

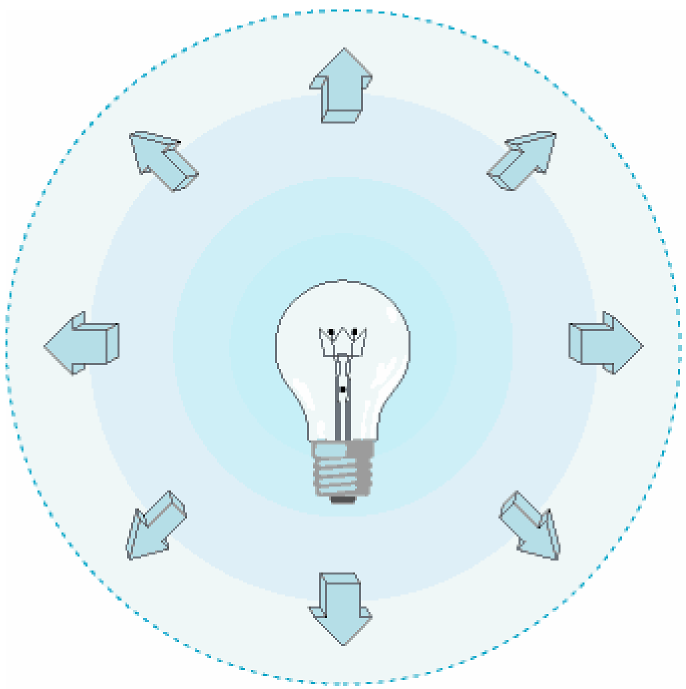
1 lumen per m^2 = 1 lux

1 ft^2 at a distance of 1 ft subtends 1 sr
(ω = 1 ft^2/ 1 ft^2 = 1 steradian)
1 cd source emits 1 lumen into 1 sr
1 lumen per ft^2 = 1 foot-candle (fc)

1 ft^2 = 0.0929 m^2

The foot-candle contains 10.76 times more light per unit area than the lux

Inverse-Square Law



Since light from a "point source" expands outward, illuminance available to a surface decreases according to the inverse-square law

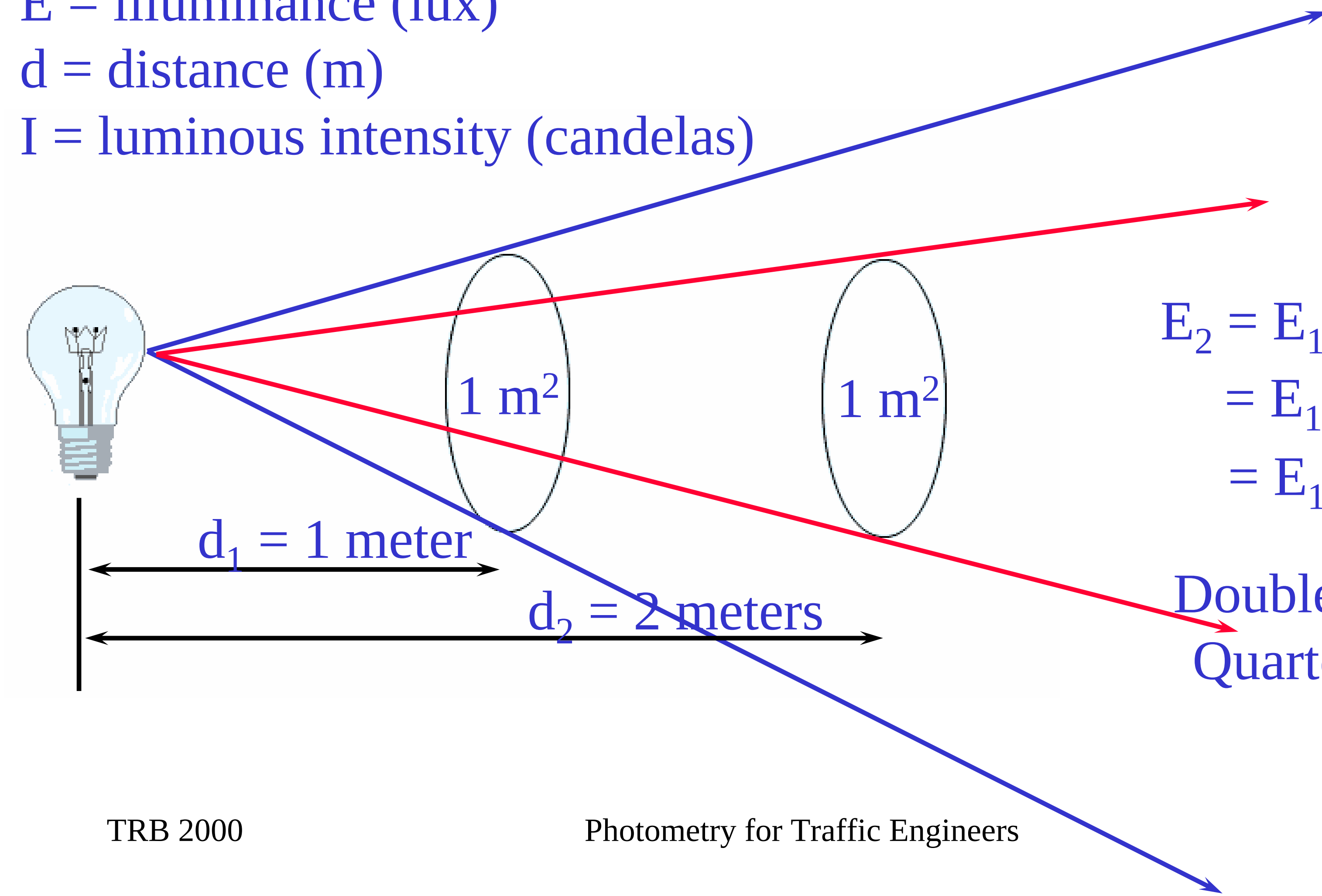
An illuminaire can be treated as a "point source" when the viewing distance is at least 5X greater than the diameter of the light source (5-to-1 rule)

Inverse-Square Law Example

$$\mathbf{E = I/d^2 \cdot \cos(\theta) \quad E_1\, d_1^2 = E_2\, d_2^2}$$

where:

- E = illuminance (lux)
- d = distance (m)
- I = luminous intensity (candelas)



$$E_2 = E_1\, d_1^2/d_2^2$$
$$= E_1 * 1/2^2$$
$$= E_1/4$$

Double the distance,
Quarter the energy

Cosine Law

Illuminance also decreases with the angle of incidence, as captured by the cosine law

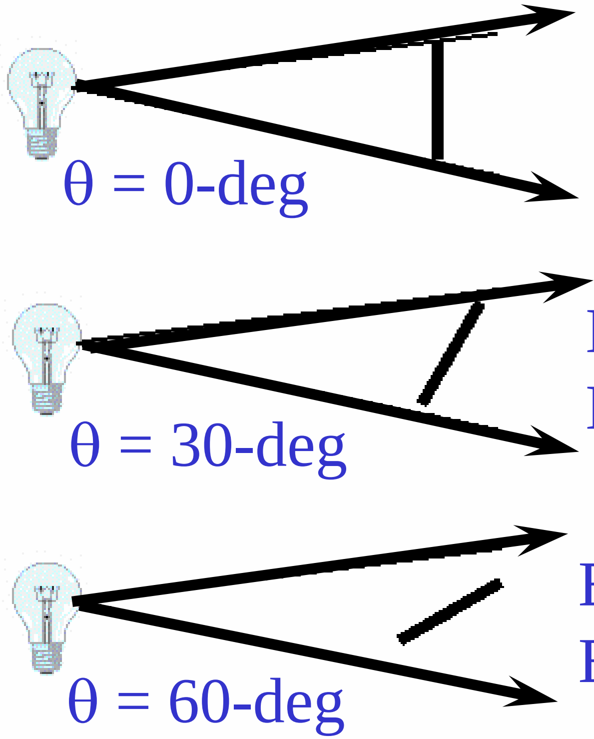
$$E_\theta = \cos(\theta) * E_0$$

where:

E_θ = Illuminace resulting from light incident at an angle θ degrees from the normal

E_0 = Illumination resulting from light incident perpendicular (normal) to the surface plane

Cosine Law Example



$E_\theta = \cos(0) * E_0$

$E_\theta = 1.0 * E_0$

$E_\theta = \cos(30) * E_0$

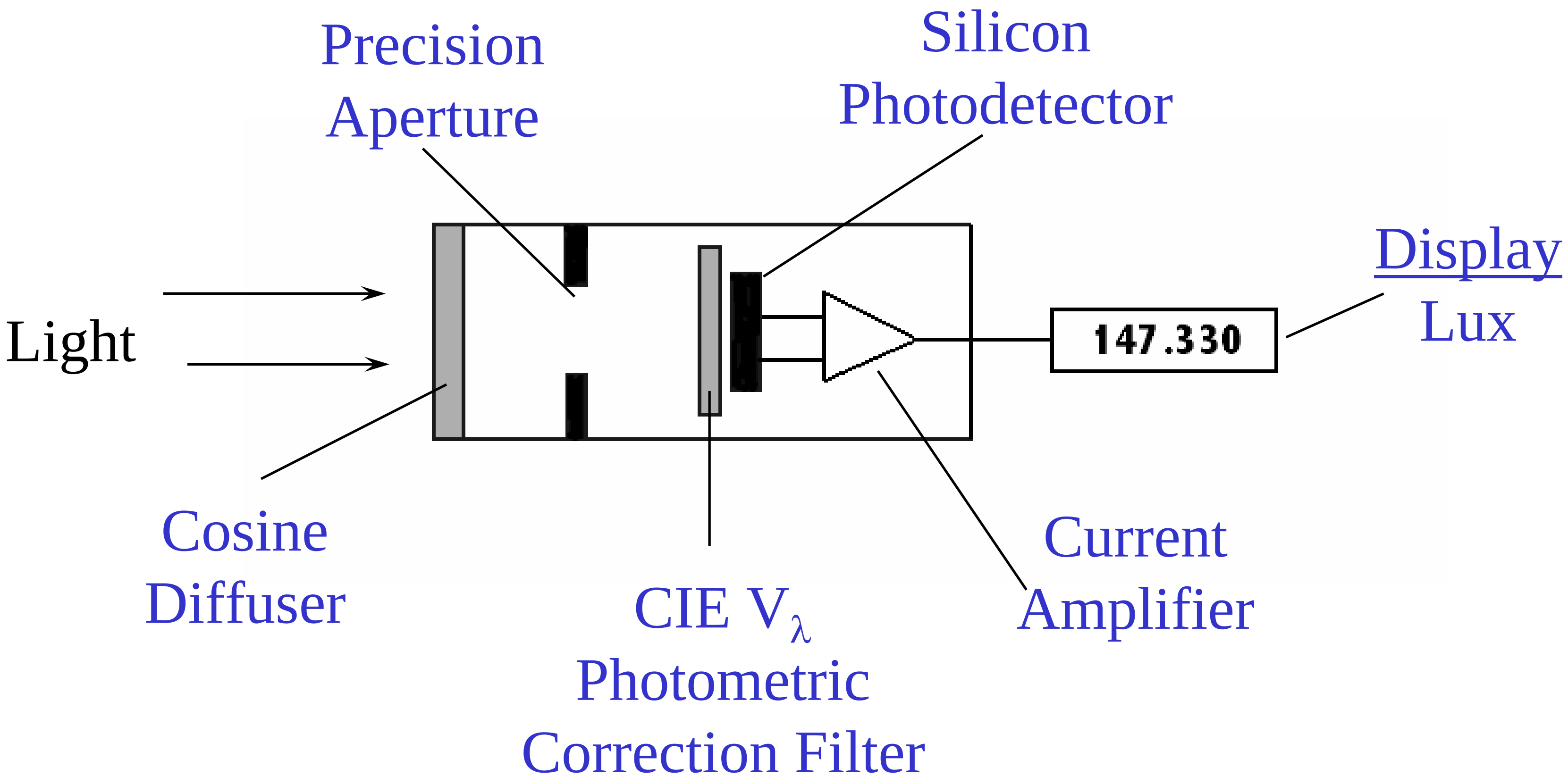
$E_\theta = 0.86 * E_0$

$E_\theta = \cos(60) * E_0$

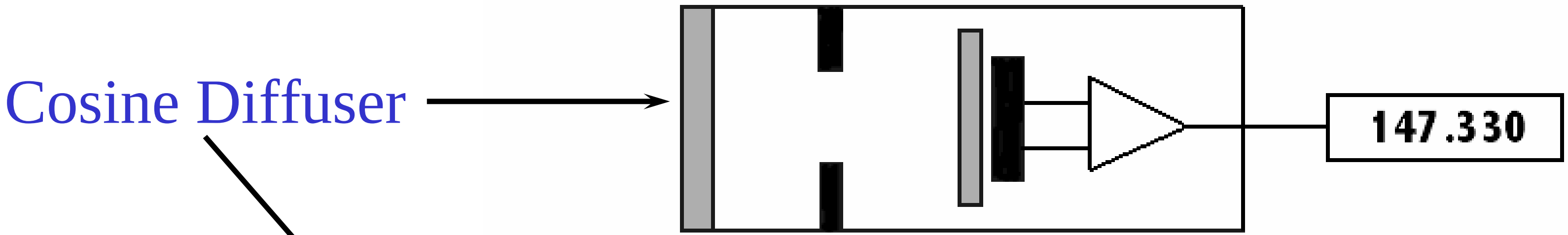
$E_\theta = 0.50 * E_0$

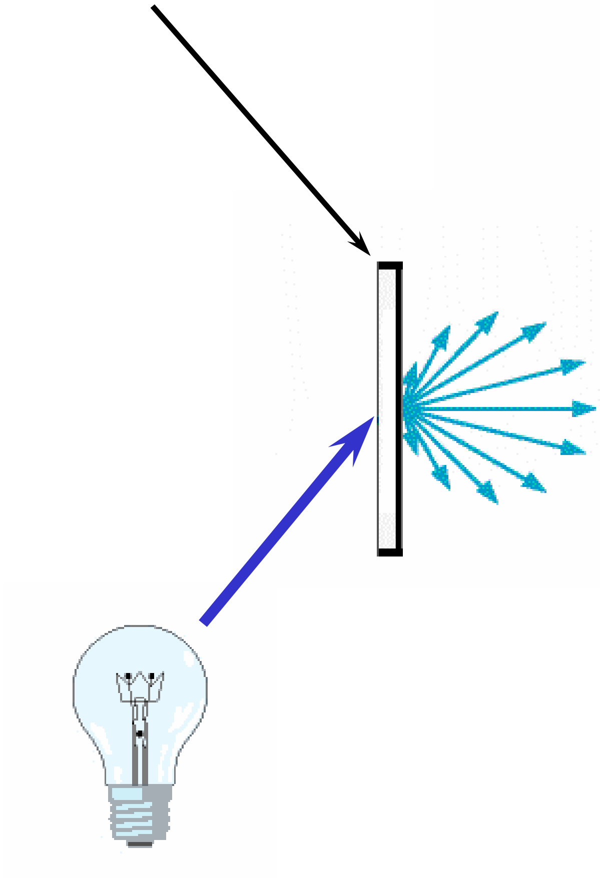
As the angle of incidence increases from 0-degrees (normal) to 90-degrees, the light density falling upon a surface drops by a factor of $\cos(\theta)$

Broadband Photometer (Illumination Meter)



Cosine Diffuser Head





Precision diffusion “lens” can redirect off-axis light toward the detector while also effectively applying the cosine correction factor

Luminance
(Candelas/m^2)

Luminance

Luminance is a measure of the:

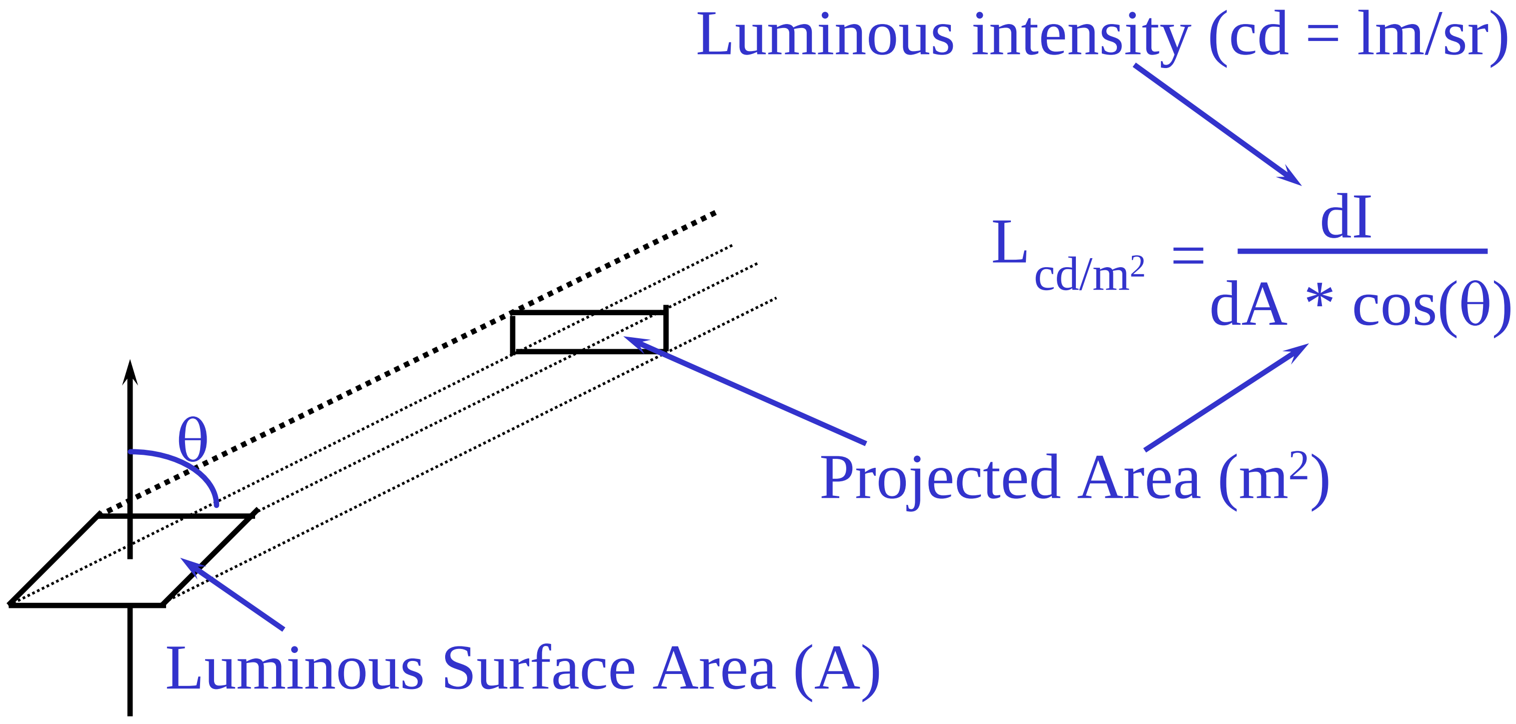
- luminous flux density per beam solid angle

- areal density of luminous intensity emitted from an extended source

- luminous intensity of the projected image of an extended source per unit area of that extended source

- The SI unit of luminance is the candela per m^2

Luminance
as
Projected Luminous Intensity



$$L_{cd/m^2} = \frac{dI}{dA * \cos(\theta)}$$

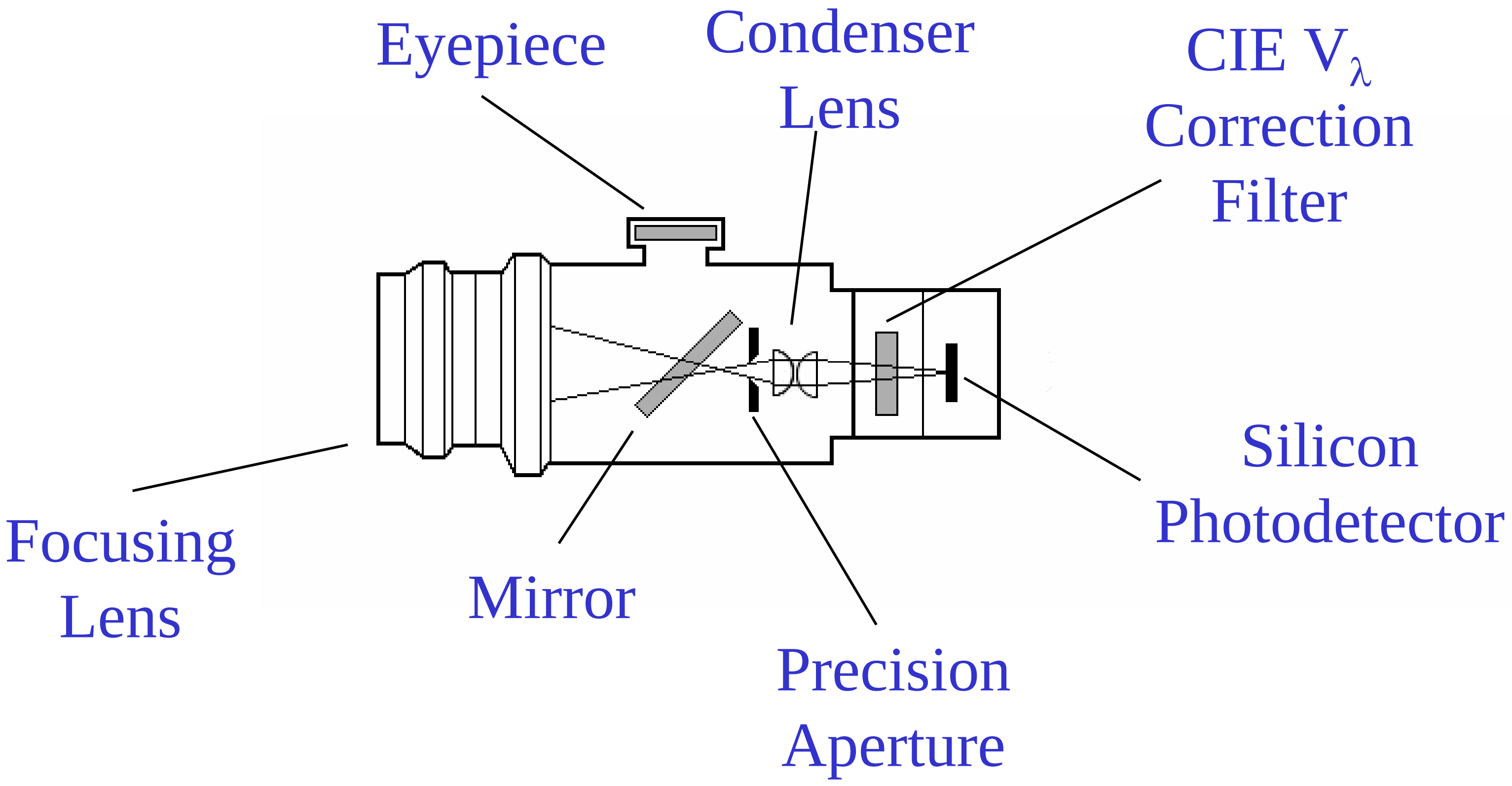
Luminance is an Abstraction

Luminance is not a source quantity nor a detector quantity; instead, it is a purely geometric quantity that describes the beam of light (areal image) connecting the source and the detector.

An optical system (e.g., eye or photometer) is needed to convert luminance into an illuminance at the detector.

Luminance is useful insofar as it correlates fairly well with the psychophysical dimensions of "brightness" and "contrast".

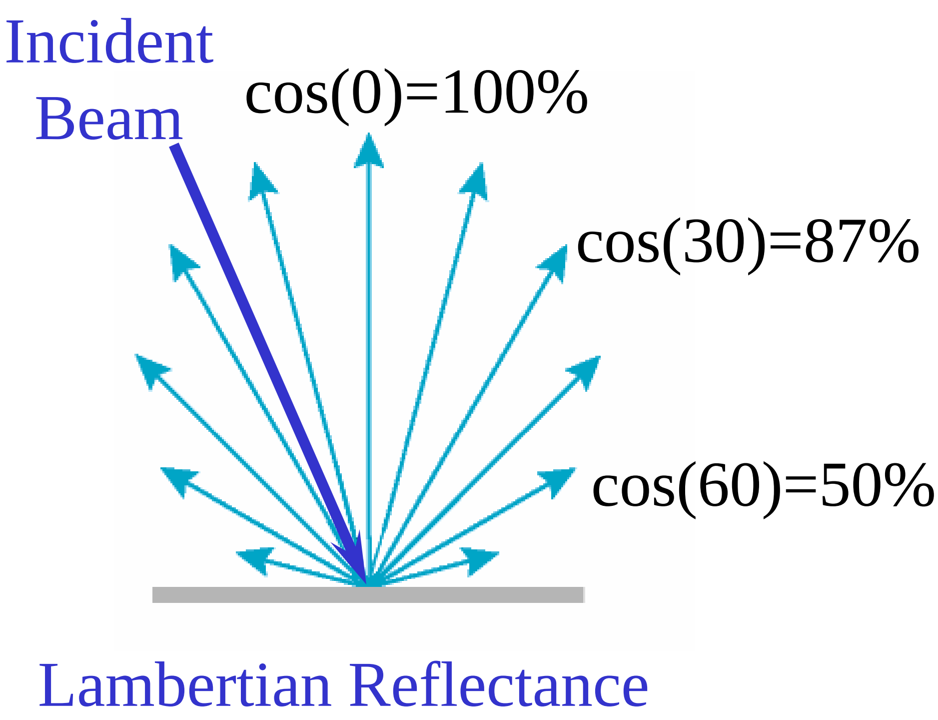
Broadband Luminance Meter

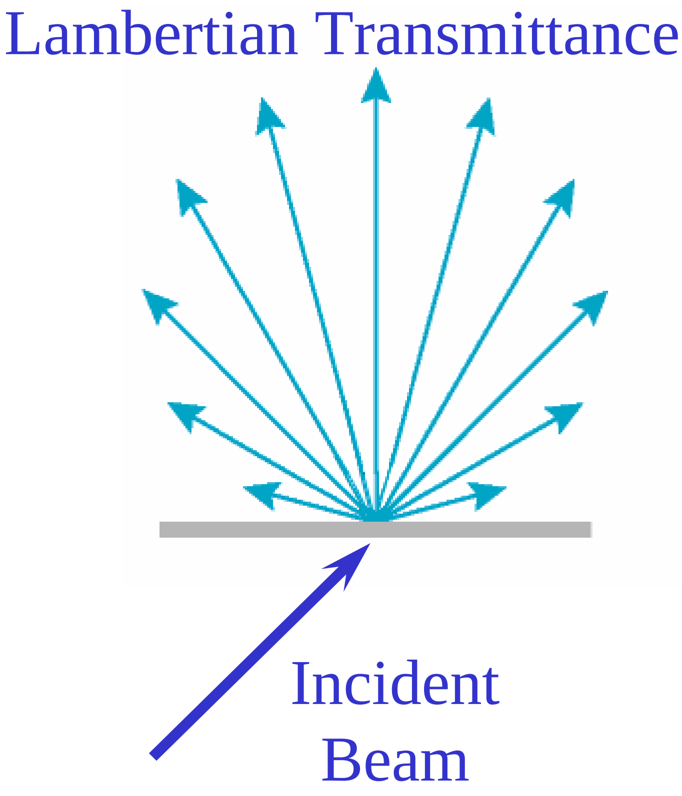


Conservation of Luminance Across Viewing Geometry

- Lambert’s Law of Surface Diffusion
- Angle of Observation
- Observation Distance

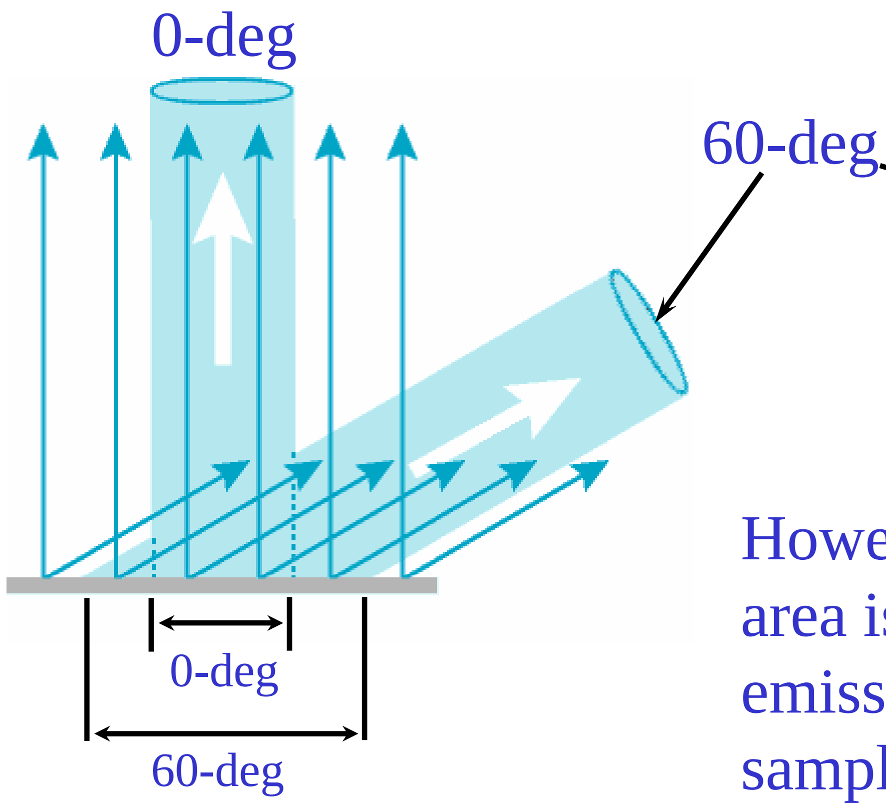
Lambertian Surface Diffusion
(Another Cosine Law)

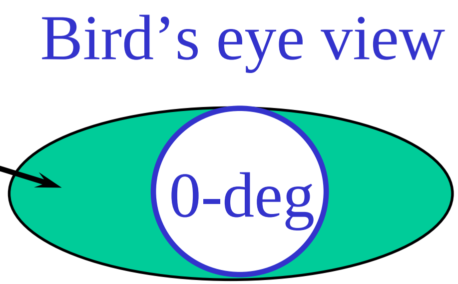




Observation Angle

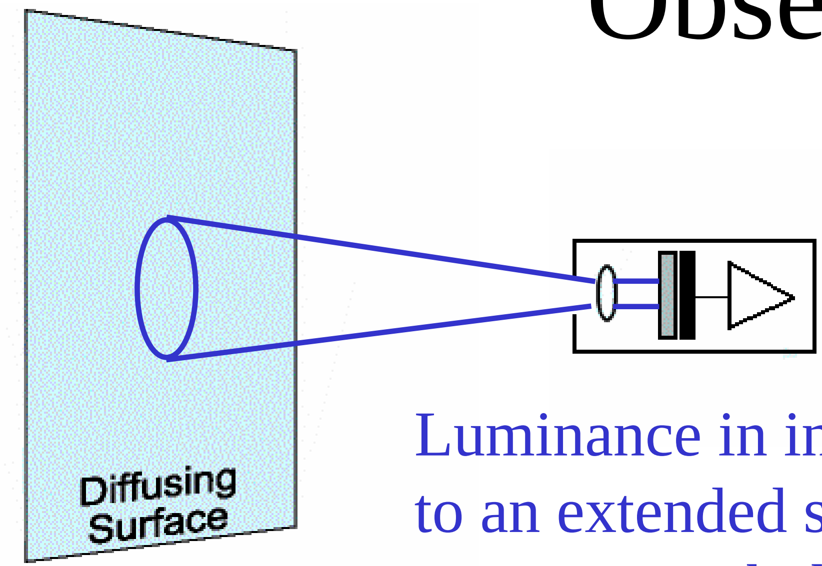
Surface area sampled through a given aperture size <u>increases</u> as a factor of cos(θ)



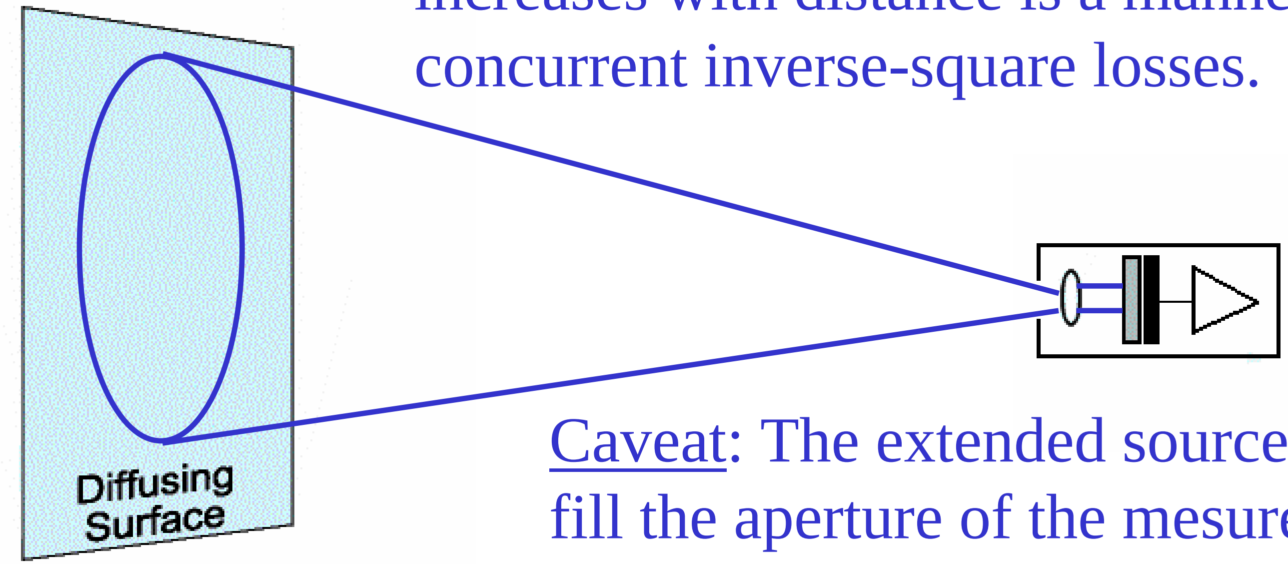


However, this increase in surface area is offset by the fact that the emission of light from the area being sampled <u>decreases</u> by the same factor of cos(θ)

Observation Distance



Luminance in independent of viewing distance to an extended source since the sampled area (FOV) increases with distance is a manner that cancels-out concurrent inverse-square losses.

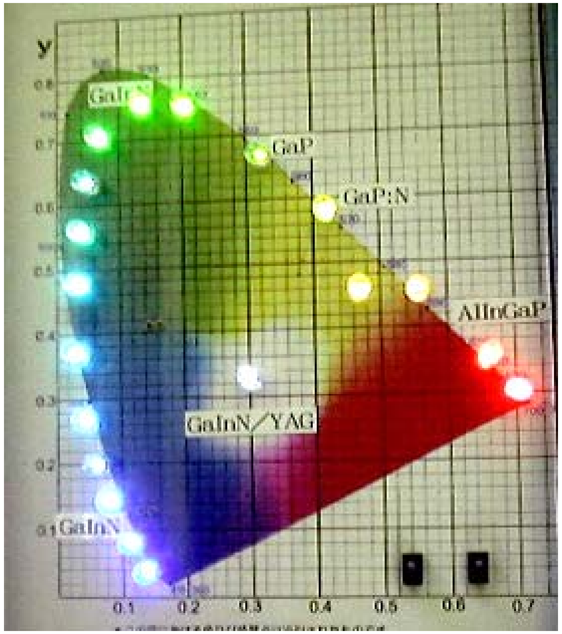


<u>Caveat</u>: The extended source must completely fill the aperture of the mesurement device!

Special Problems: LED Symbol Heads

How do you obtain a useful photometric field quantity to characterize LED-based symbol signs?

Light Emitting Diodes (LED's)



What other problems do LED's present regarding their photometric characterization?

References

- DeCusatis, C. (Editor). Handbook of Applied Photometry. New York: Springer-Verlag, 1998. [Am. Inst. Physics]

- Ryer, A. Light Measurement Handbook. http://www.intl-light.com/handbook/

- Photometry for Traffic Engineers Web Page http://www.usd.edu/~schieber/trb2000/