

Photometry for Traffic Engineers...

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

by

Frank Schieber

Heimstra Human Factors Laboratories
University of South Dakota

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

Basic Light Measurement

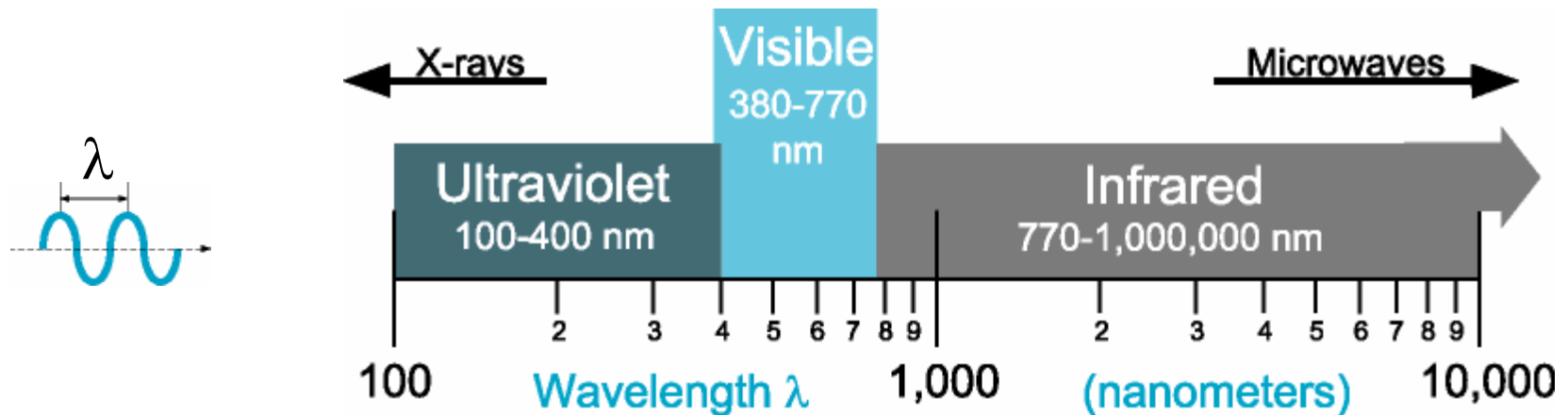
- Visible Electromagnetic Radiation (Light)
- Radiometric to Photometric Conversion
- Luminous Flux (Lumens)
- Luminous Intensity (Candela)
- Illuminance (Lux)
- Luminance (cd/m^2)

Taxonomy of Photometric Units

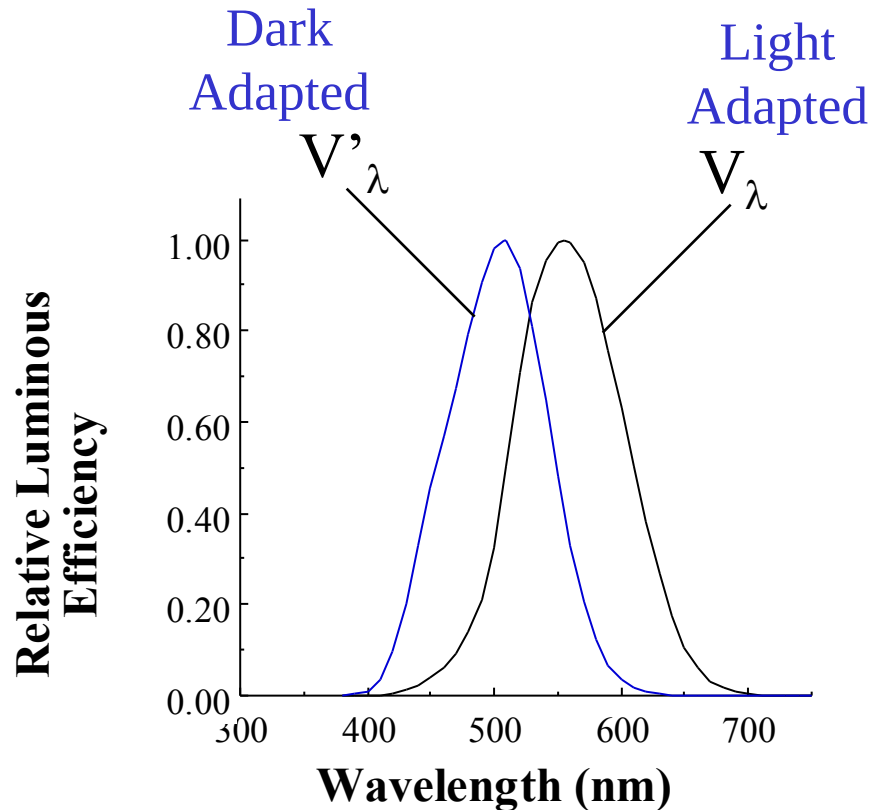
<u>Luminous Flux</u>	Lumen	Total “effective” output of a lamp
<u>Luminous Intensity</u>	Candela	Light density through space • Vehicle headlamps • Traffic signal lamps/lenses
<u>Illuminance</u>	Lux	Light density falling upon a surface • Roadway illumination • Highway sign illumination
<u>Luminance</u>	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 (400-700 nominal)
- Frequency: 789 down to 384 THz

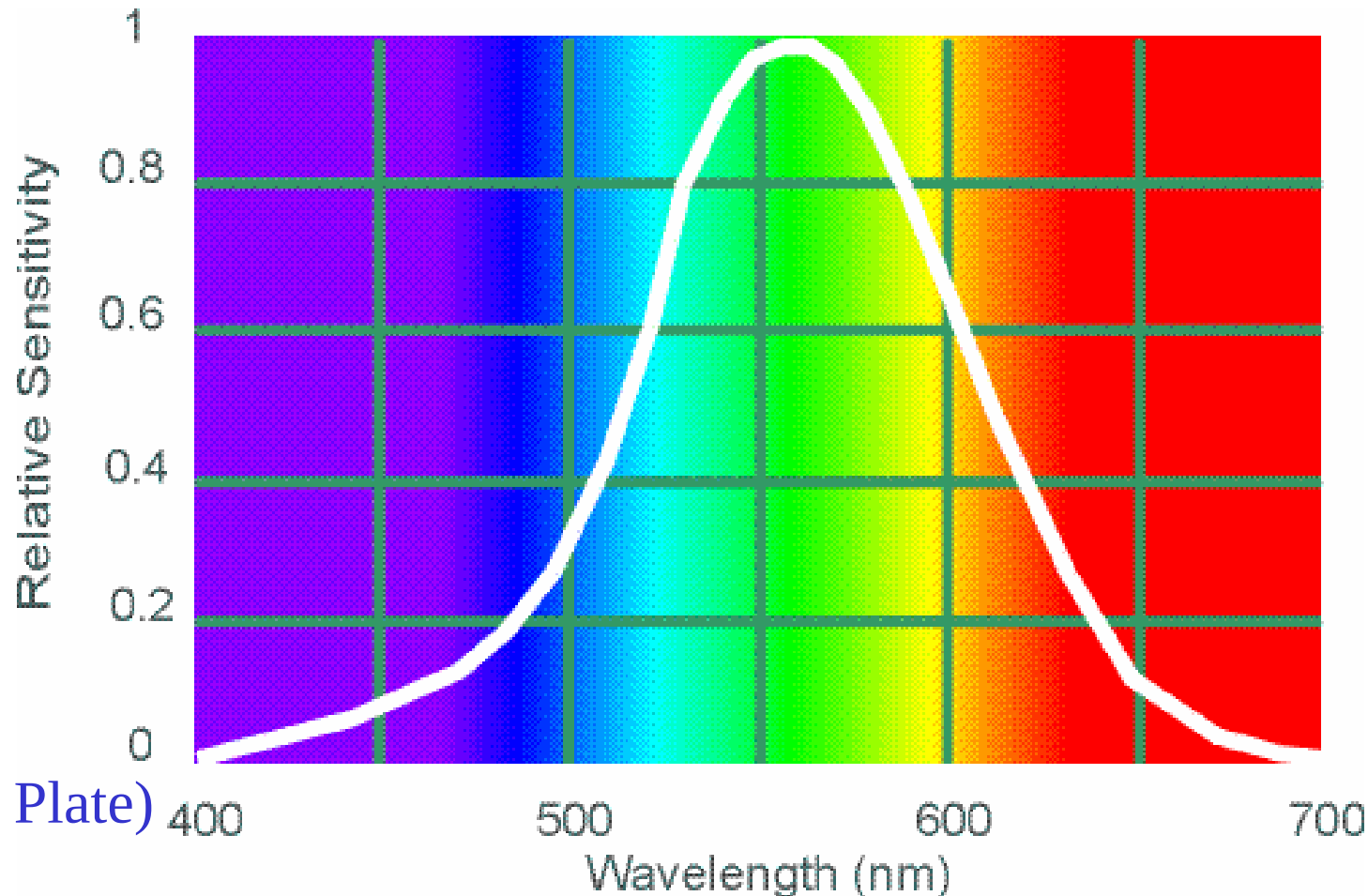


CIE Spectral Luminosity Function



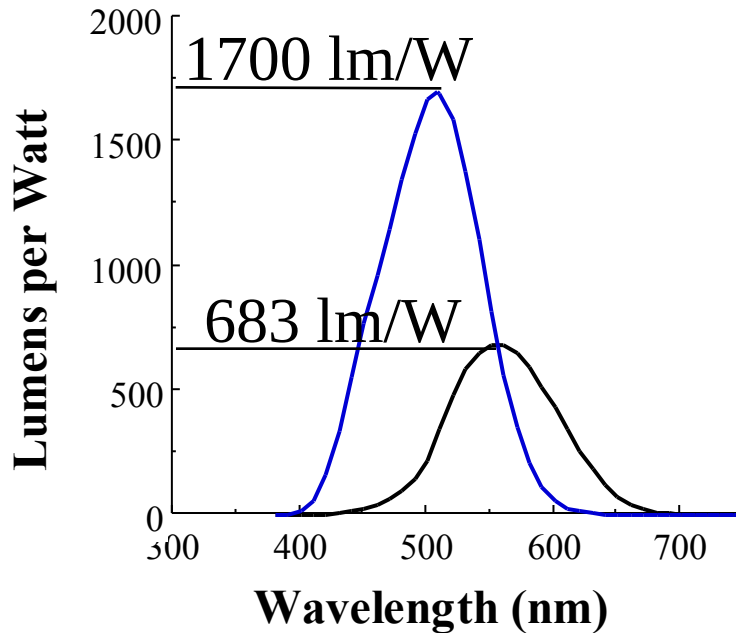
- The human eye is more sensitive to some visible wavelengths than others
- Measurements of light must take these effects into account
- CIE V_λ curve corrects for the differences across wavelengths

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 $\lambda = 507$ nm

$K_m = 1700$ lm/W

2.5 X Sensitivity

Photopic (V_λ)

Light Adapted

Peak $\lambda = 555$ 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

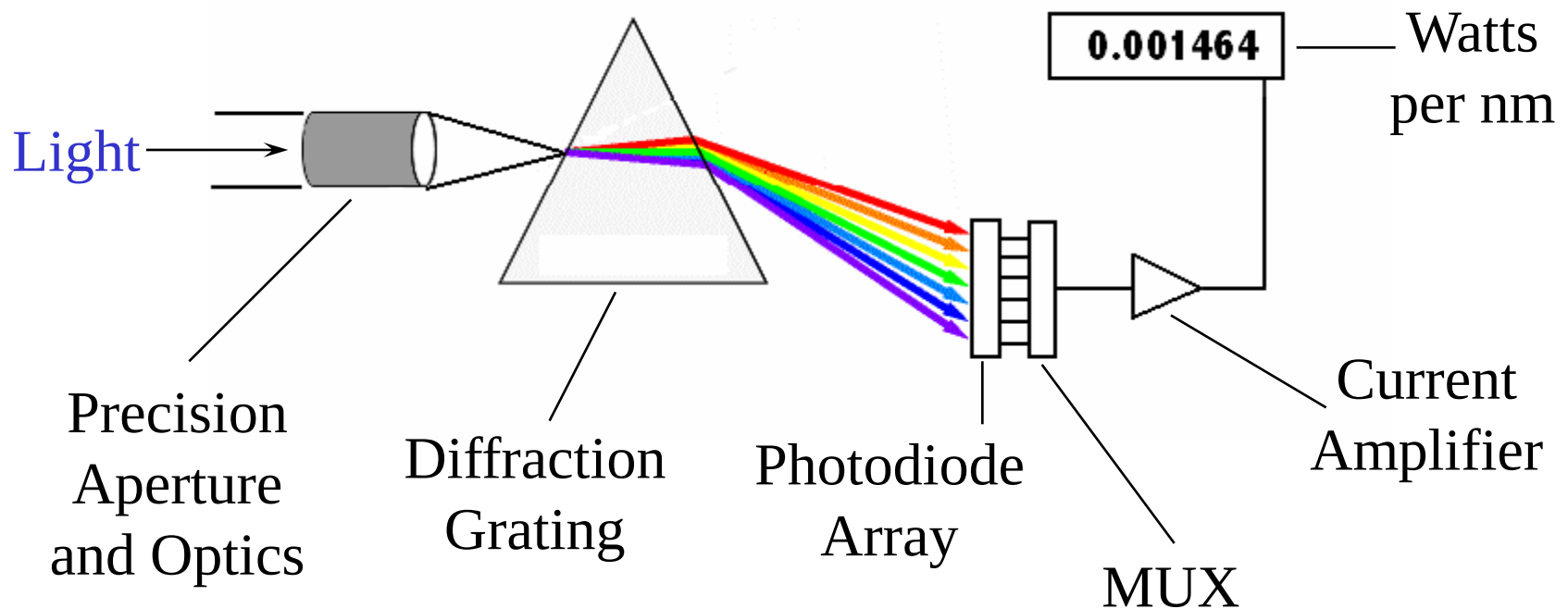
CIE
Spectral Luminosity
Function

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

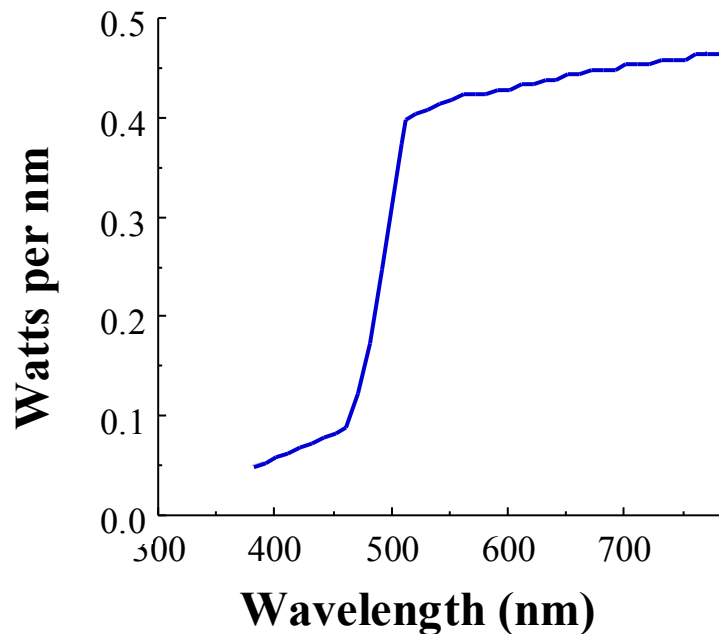
Step 1.

Measure Radiant Energy across λ using a Spectroradiometer



(See next slide for sample data)

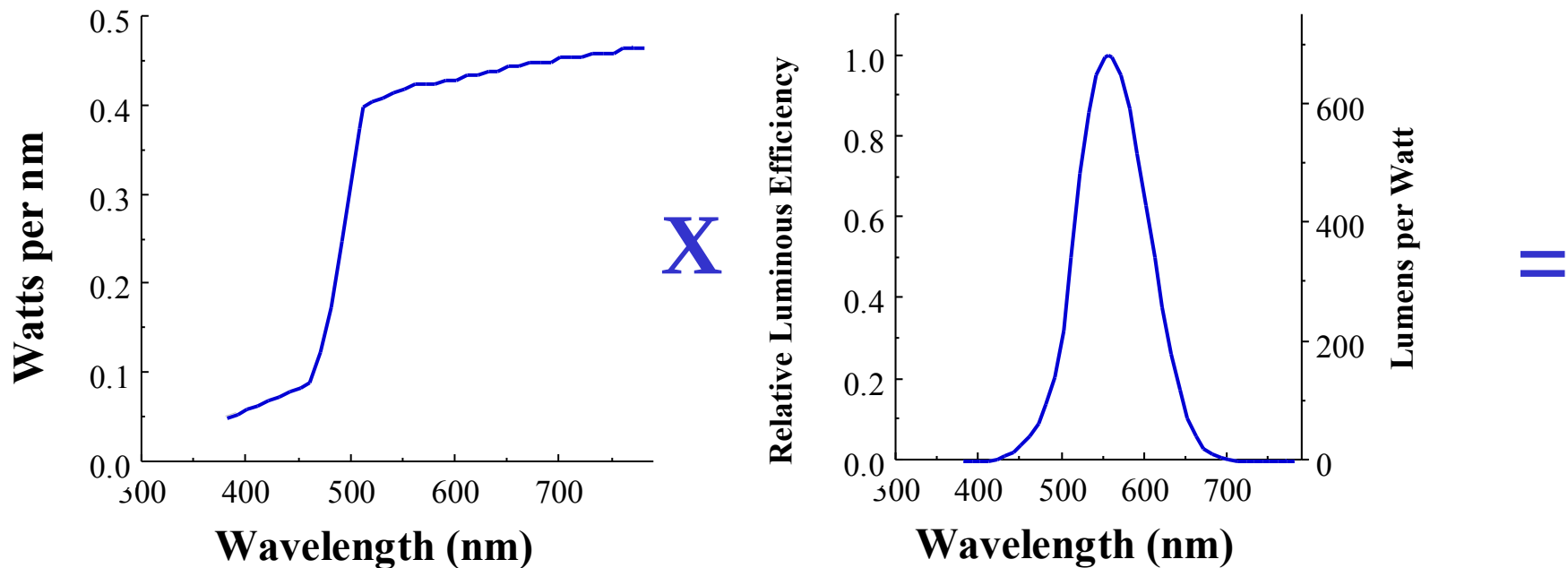
Sample Data from Spectroradiometer



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

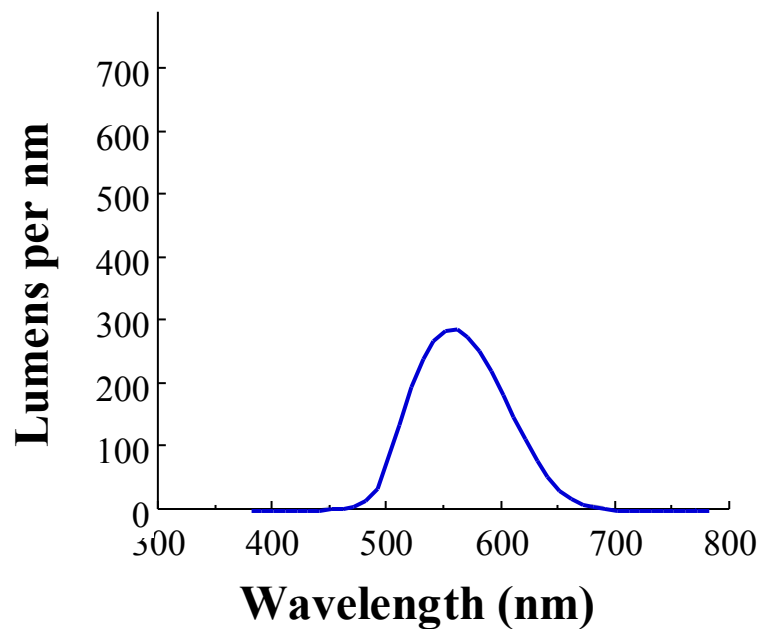
Step 2.

Convert Watts to Lumens



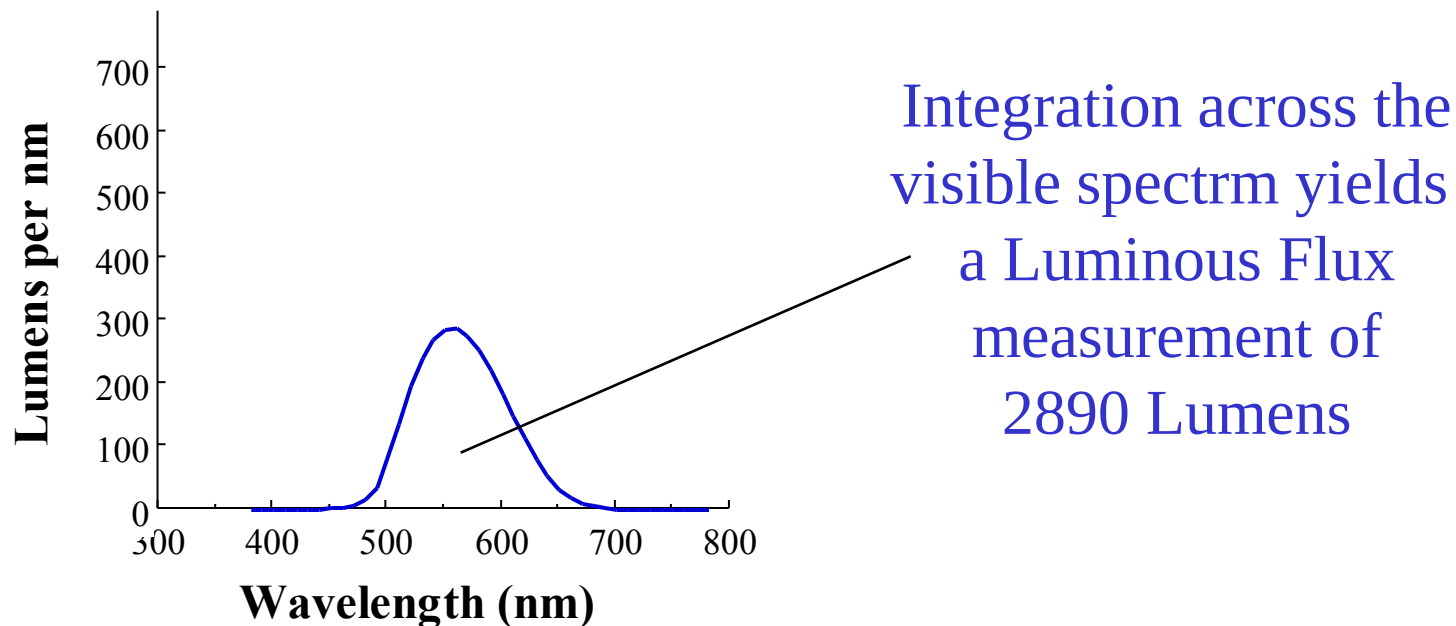
(See next slide for results)

Results of V_λ Conversion



Step 3.

Integrate Lumens from 380-730 nm



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

(Power of Directional Beams)

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

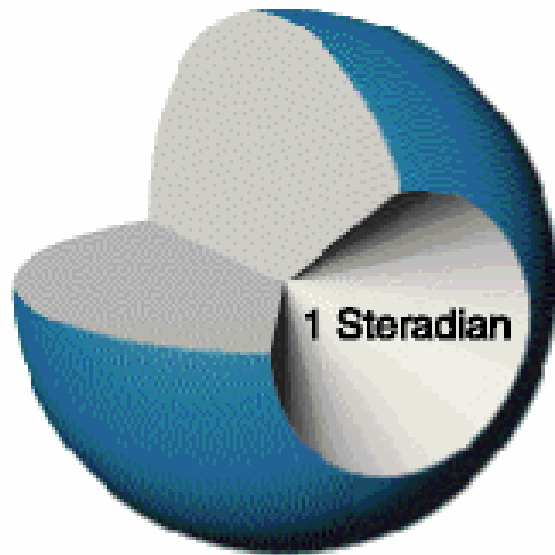
The candela is historically linked to “candle power” (ie., 1/683 W/sr at 555 nm)

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

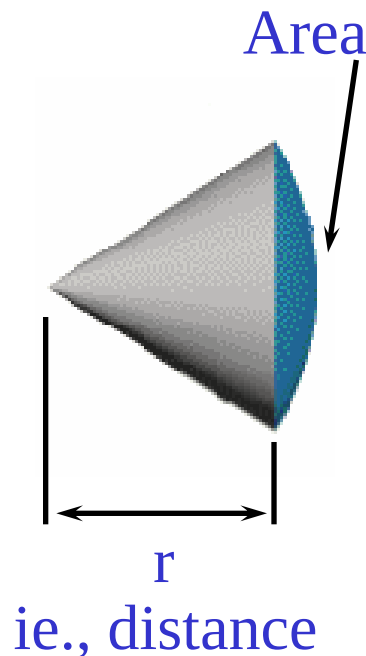
← steradian

Solid Angles, Surfaces of Spheres and the Steradian

Imaginary Sphere Surrounding
a point source of light



$$\text{Sphere Area} = 4\pi r^2$$



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

1 m² subtends 1 sr at a
distance of 1 m...since

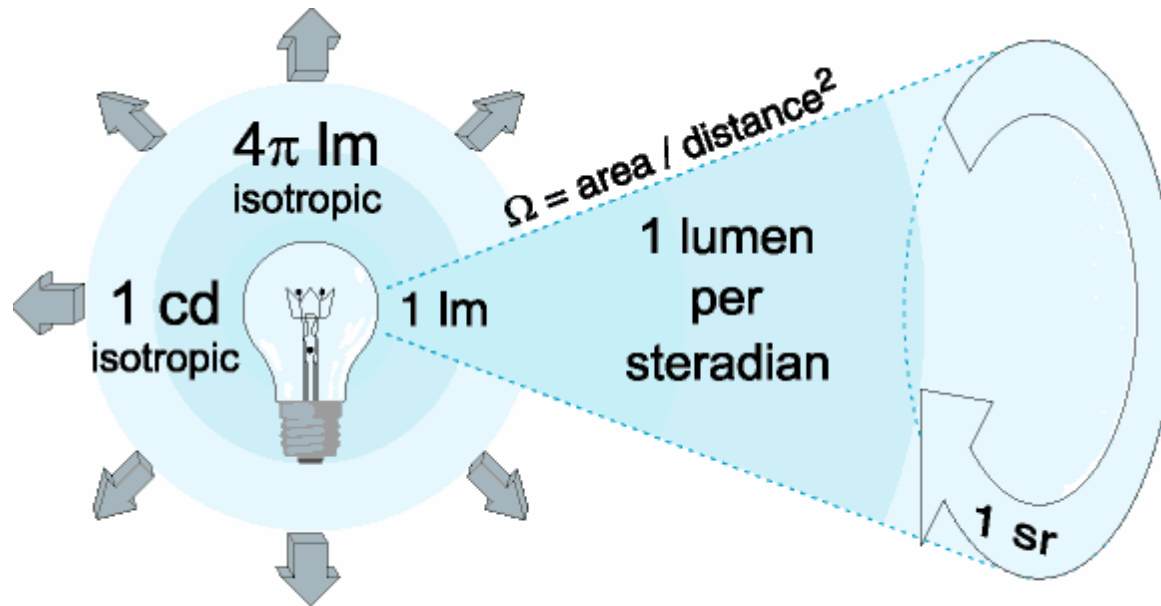
$$\omega = \frac{A}{r^2} = \frac{1 \text{ m}^2}{1 \text{ m}^2} = 1$$

Surface area of a sphere
is subtended by 4π sr

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

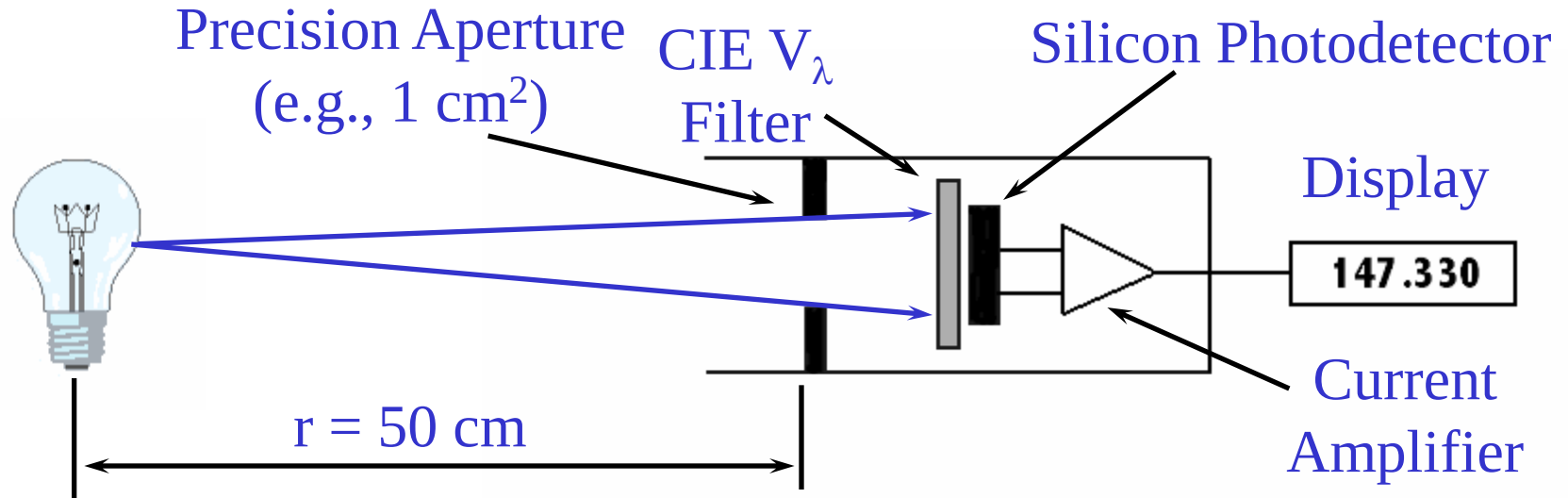
$$4\pi = 12.56$$

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

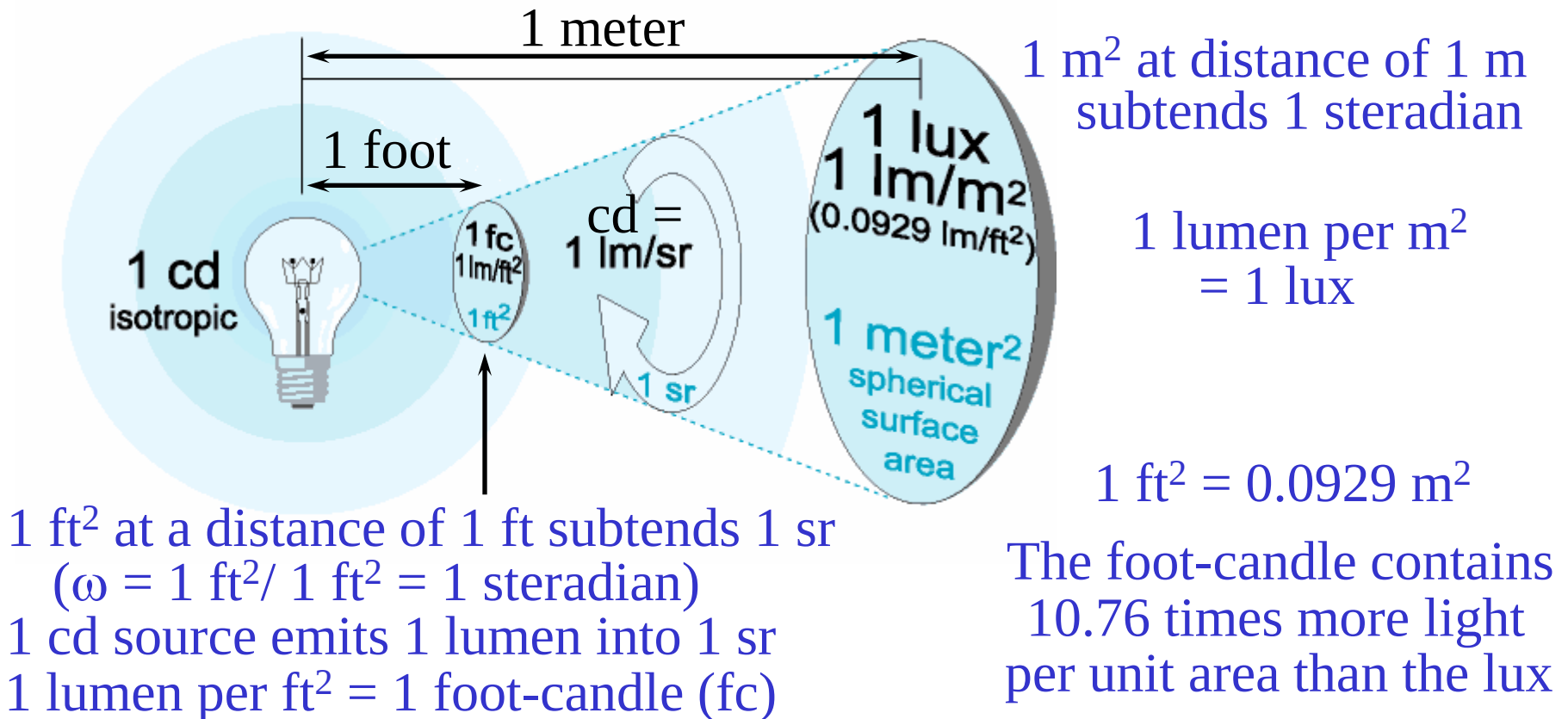


- Photometer aperture subtends 0.0004 sr at 50 cm distance
($\omega = \text{Area} / r^2 = 1 \text{ cm}^2 / (50 \text{ cm})^2 = 0.0004 \text{ sr}$)
- Light energy in 0.0004 sr is filtered and converted to current
- Current is converted to lumens (per calibration constant)
- Lumens divided by $0.0004 \text{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

Illuminance (Lux)

Illuminance

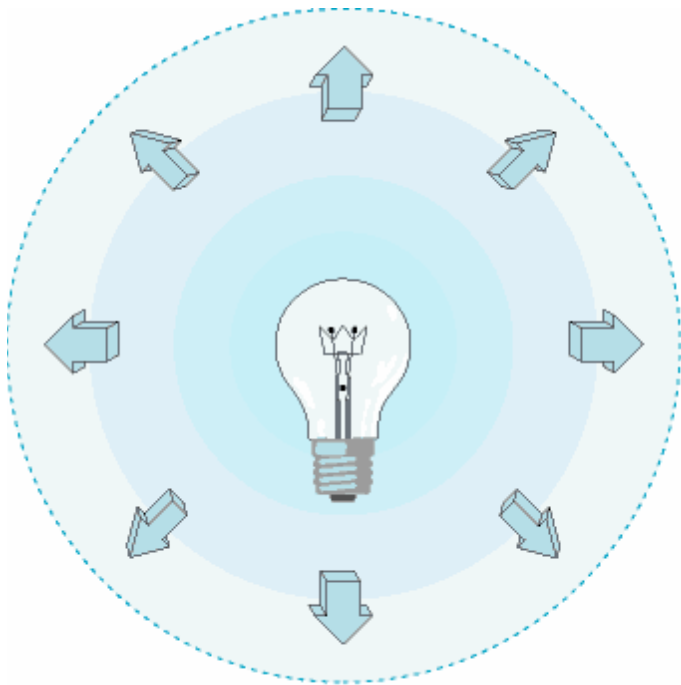
The photometrically corrected light energy falling upon a given unit of surface area (e.g. lumens/m²)



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

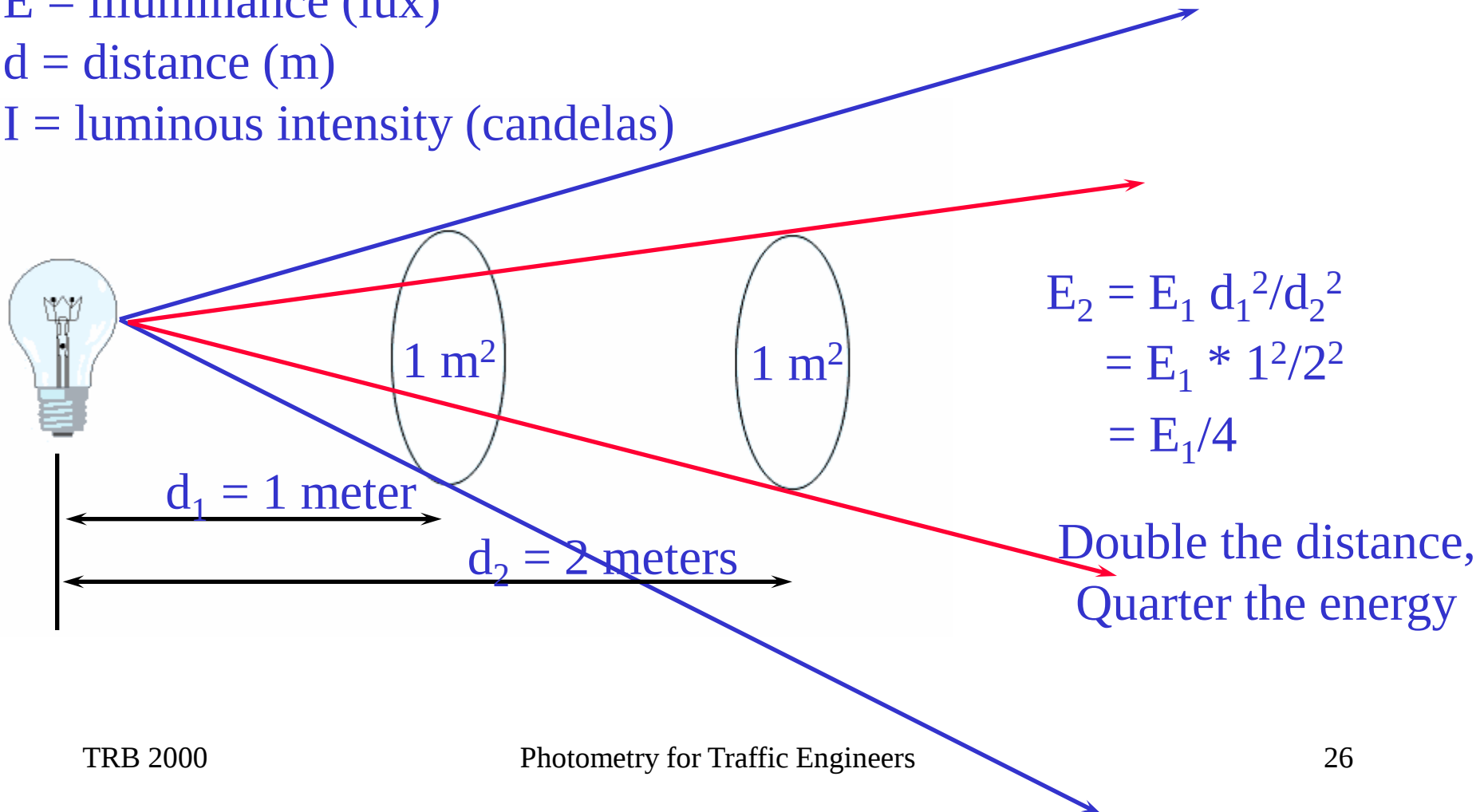
$$E = I/d^2 \cdot \cos(\theta); \quad E_1 d_1^2 = E_2 d_2^2$$

where:

E = illuminance (lux)

d = distance (m)

I = luminous intensity (candelas)



Cosine Law

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

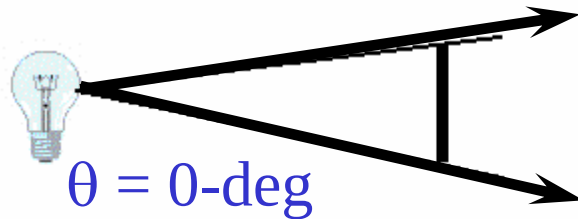
$$E_{\theta} = \cos(\theta) * E_0$$

where:

E_{θ} = Illuminance 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



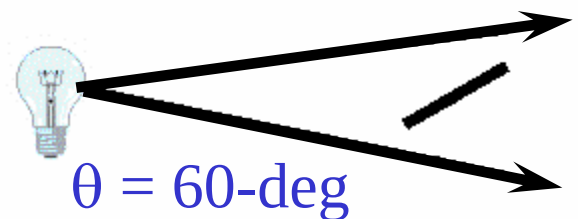
A light source (light bulb) is shown on the left. Two parallel arrows representing light rays point to the right. A vertical line segment, representing the normal to the surface, is drawn between the two rays. The angle between the top ray and the normal is labeled $\theta = 0\text{-deg}$.

$$E_{\theta} = \cos(0) * E_0$$
$$E_{\theta} = 1.0 * E_0$$



A light source (light bulb) is shown on the left. Two parallel arrows representing light rays point to the right. A line segment, representing the normal to the surface, is drawn between the two rays. The angle between the top ray and the normal is labeled $\theta = 30\text{-deg}$.

$$E_{\theta} = \cos(30) * E_0$$
$$E_{\theta} = 0.86 * E_0$$

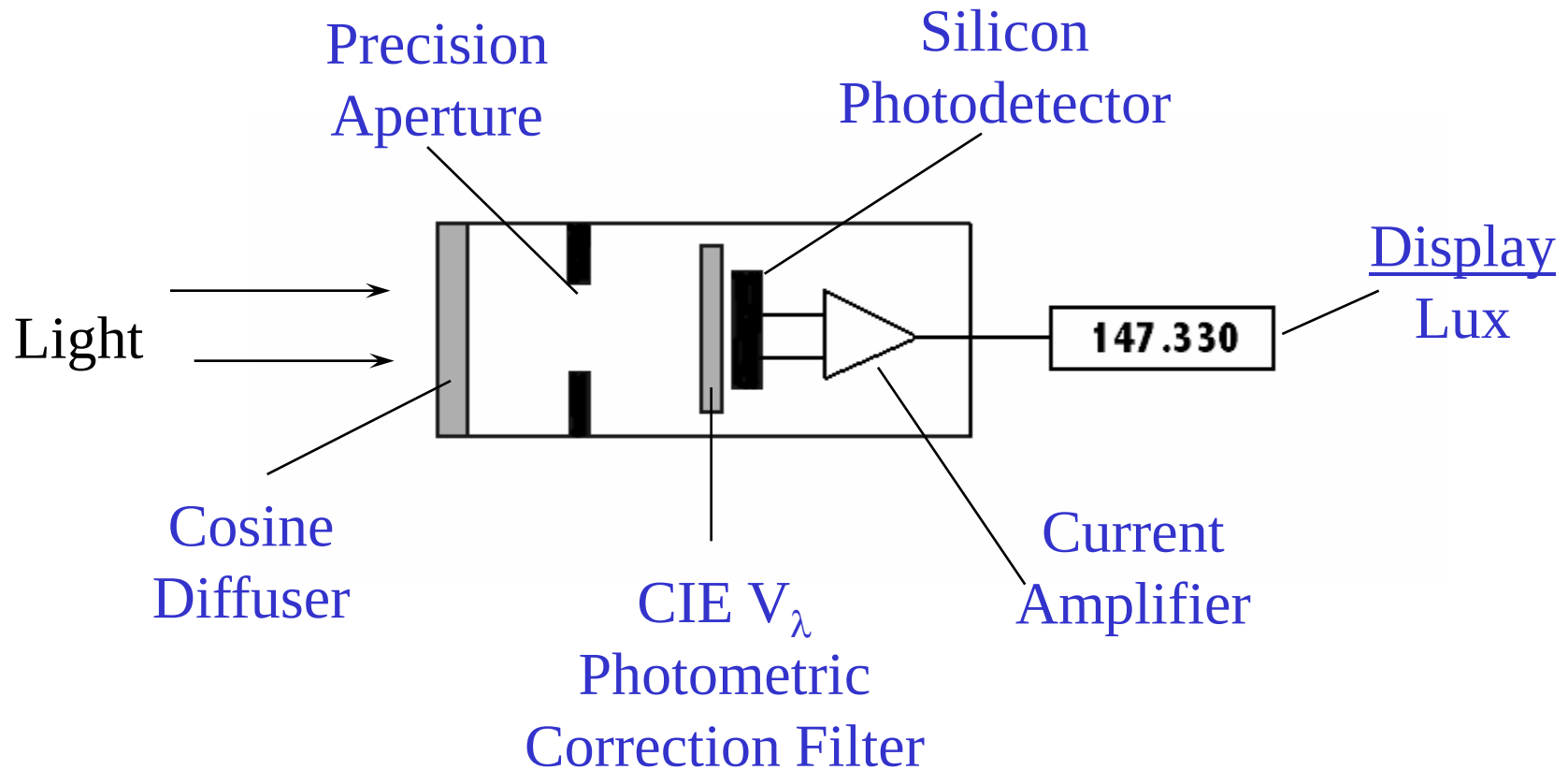


A light source (light bulb) is shown on the left. Two parallel arrows representing light rays point to the right. A line segment, representing the normal to the surface, is drawn between the two rays. The angle between the top ray and the normal is labeled $\theta = 60\text{-deg}$.

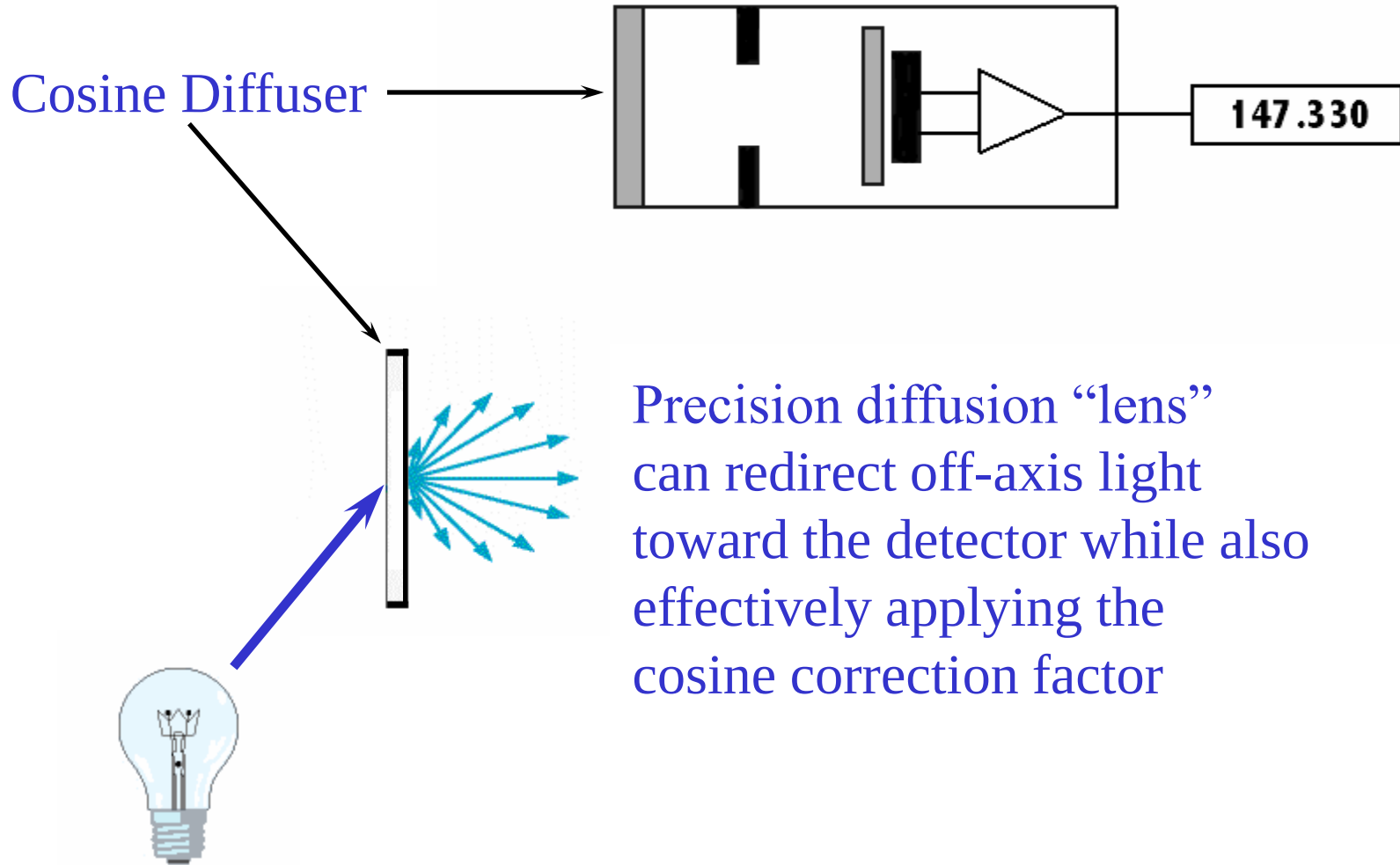
$$E_{\theta} = \cos(60) * E_0$$
$$E_{\theta} = 0.50 * E_0$$

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

Broadband Photometer (Illumination Meter)



Cosine Diffuser Head



Luminance

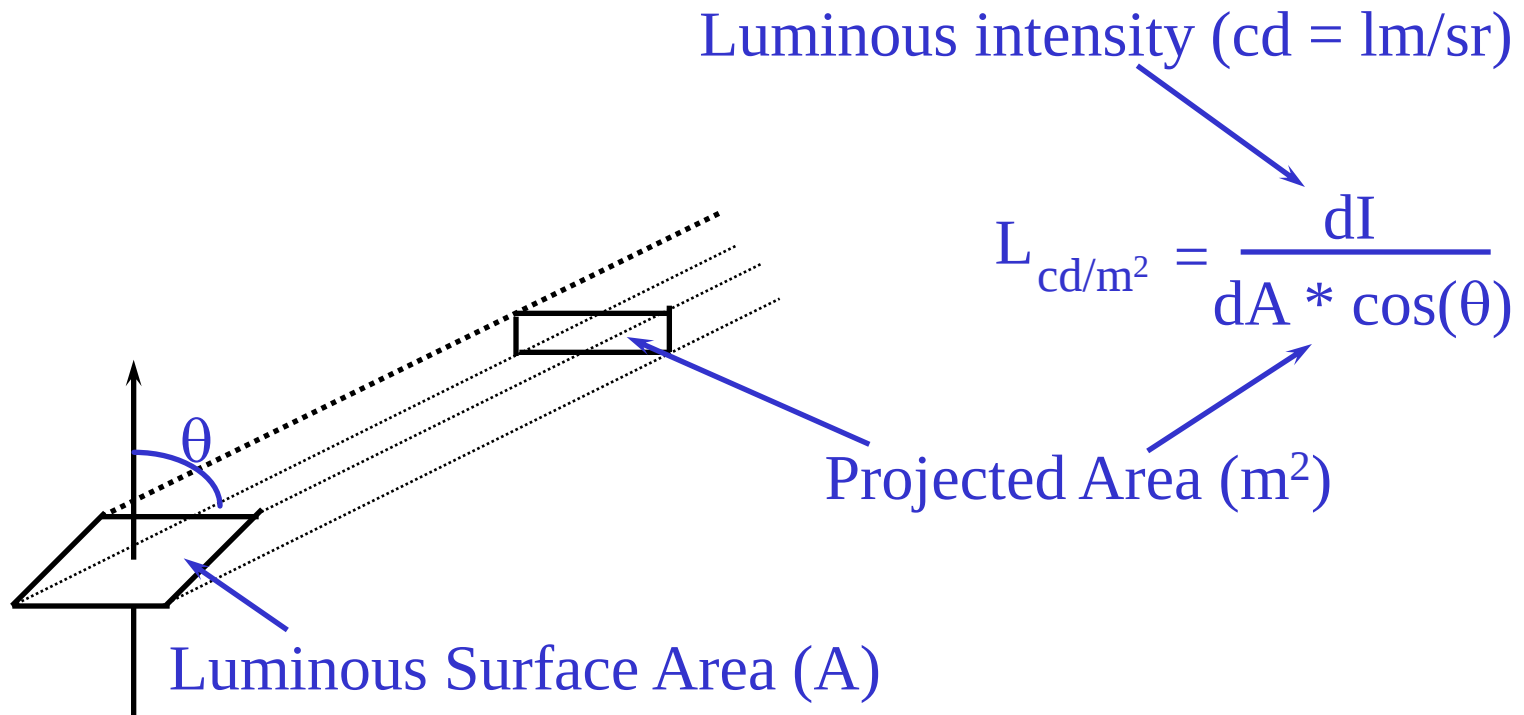
(lux/sr x 1/m²; candela/m²)

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 m² (“nit”)

Luminance as Projected Luminous Intensity



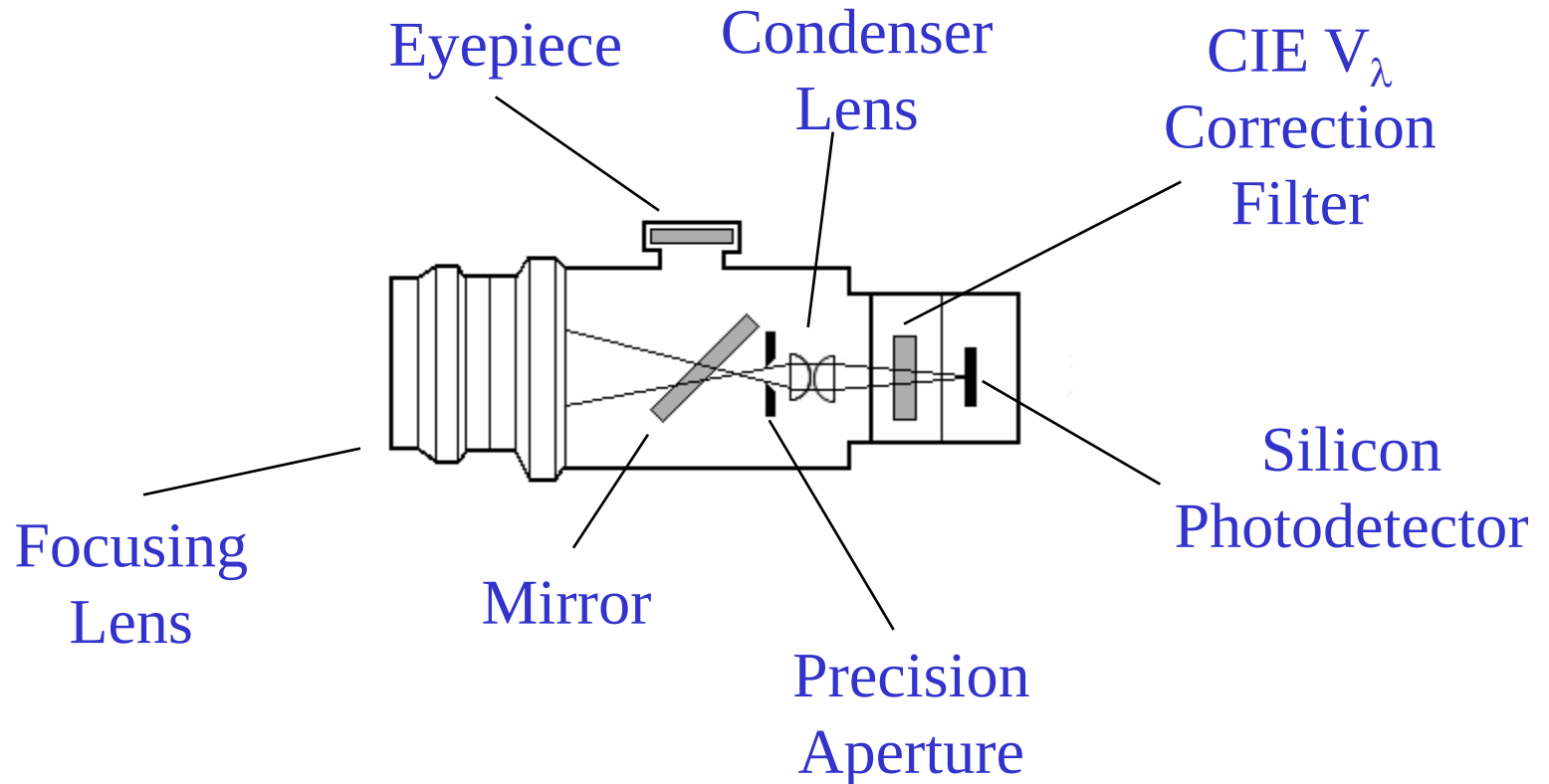
Luminance is an Abstraction

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 (e.g., retinal illuminance or “trolands”).

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

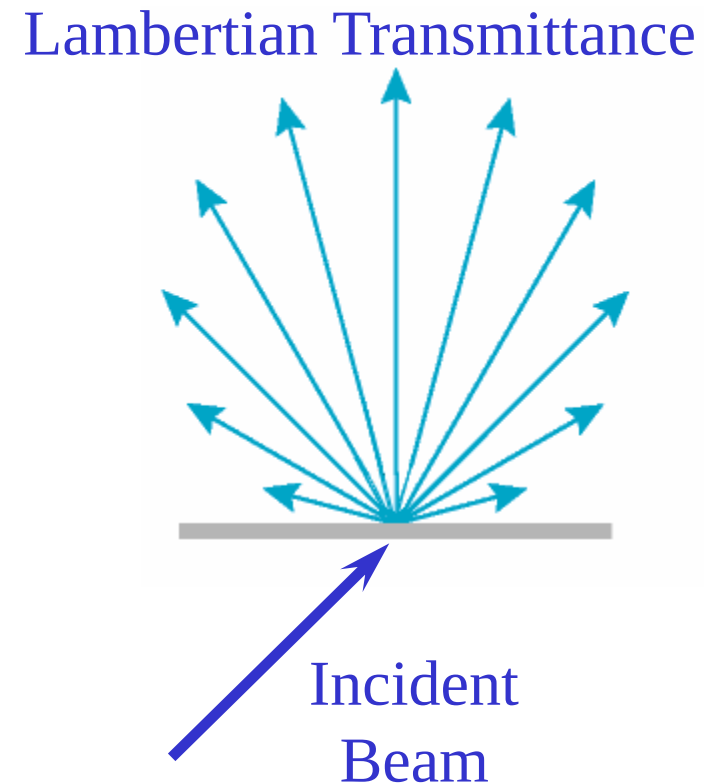
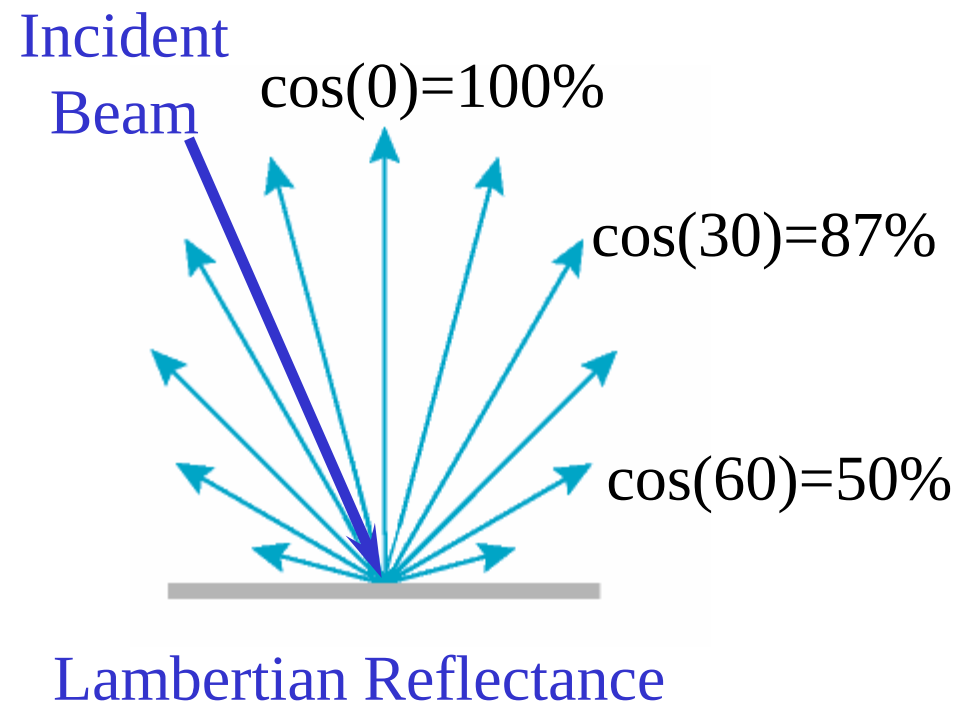
Broadband Luminance Meter



Conservation of Luminance Across Viewing Geometry

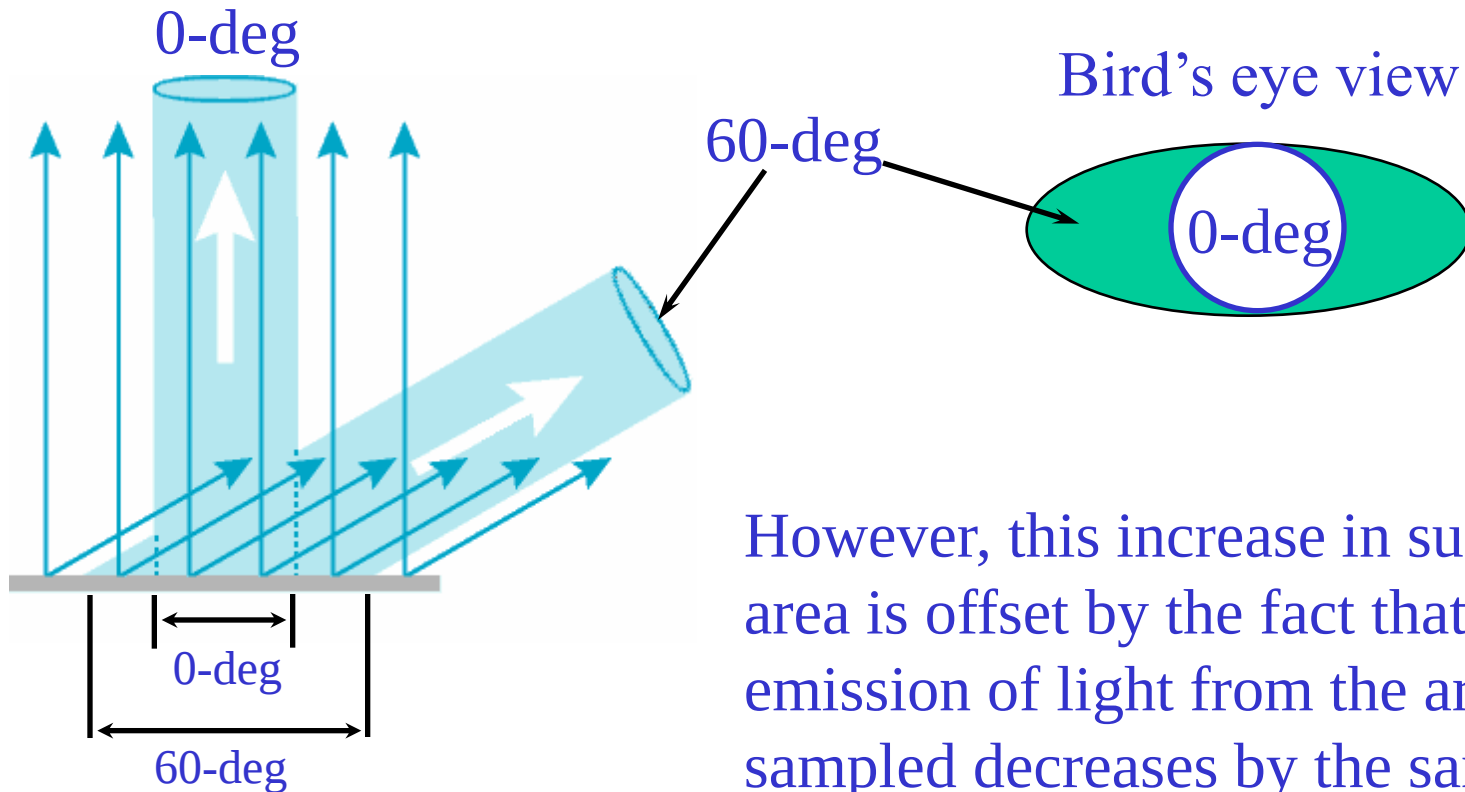
- Lambert's Law of Surface Diffusion
- Angle of Observation
- Observation Distance

Lambertian Surface Diffusion (Another Cosine Law)



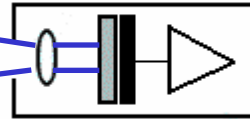
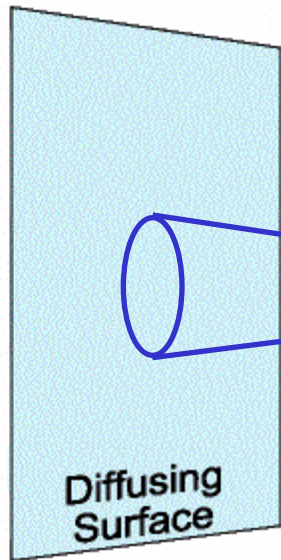
Observation Angle

Surface area sampled through a given aperture size increases as a factor of $\cos(\theta)$

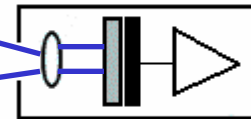
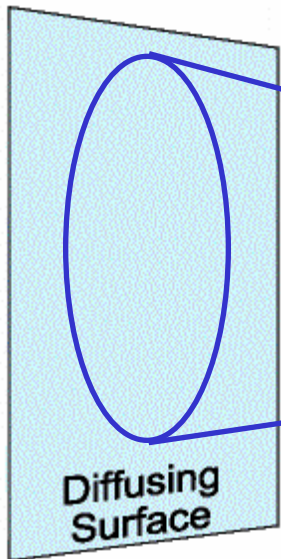


However, this increase in surface area is offset by the fact that the emission of light from the area being sampled decreases by the same factor of $\cos(\theta)$

Observation Distance



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



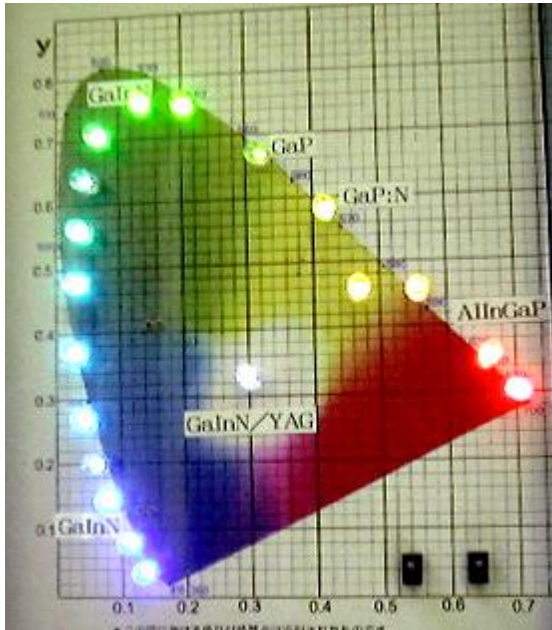
Caveat: The extended source must completely fill the aperture of the measurement device!

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/>
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- Photometry for Traffic Engineers Web Page
<http://apps.usd.edu/coglab/schieber/trb2000/index.htm>