

Computer Graphics

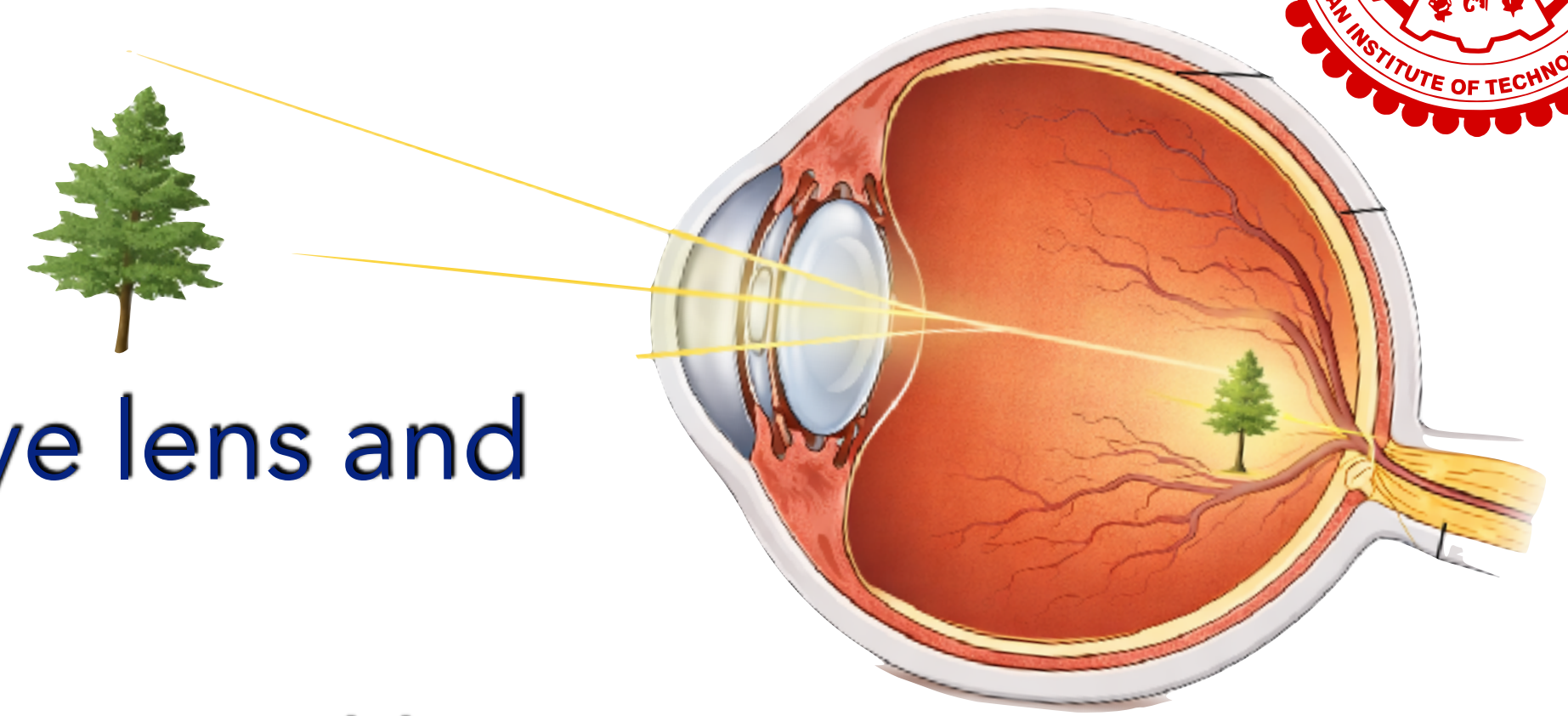
Light and Color

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Image Formation



- Light reflected by an object passes through eye lens and reaches a photoreceptor in the retina
- What is the difference if the “same” light is generated by a computer instead? Does point of origin matter?
- How to generate that many (more than $10^{20}/s$, e.g.) “same” photons?

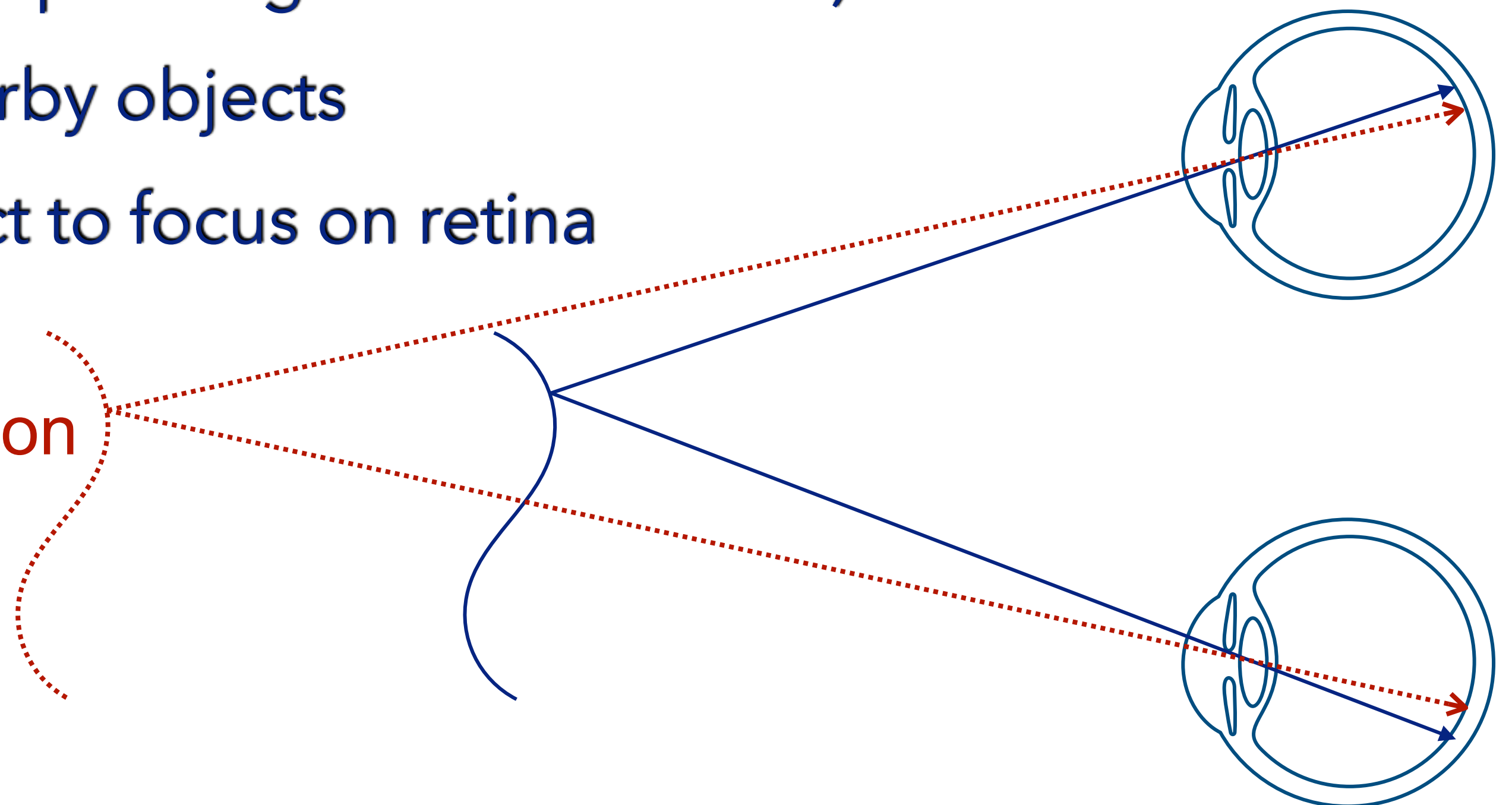


Source of Light



- Humans have stereoscopic vision
- Depth cues
 - ➔ Parallax (Relative shift with motion, depending on the distance)
 - ➔ Convergence of eye to focus on nearby objects
 - ➔ Accommodation of lens to get object to focus on retina

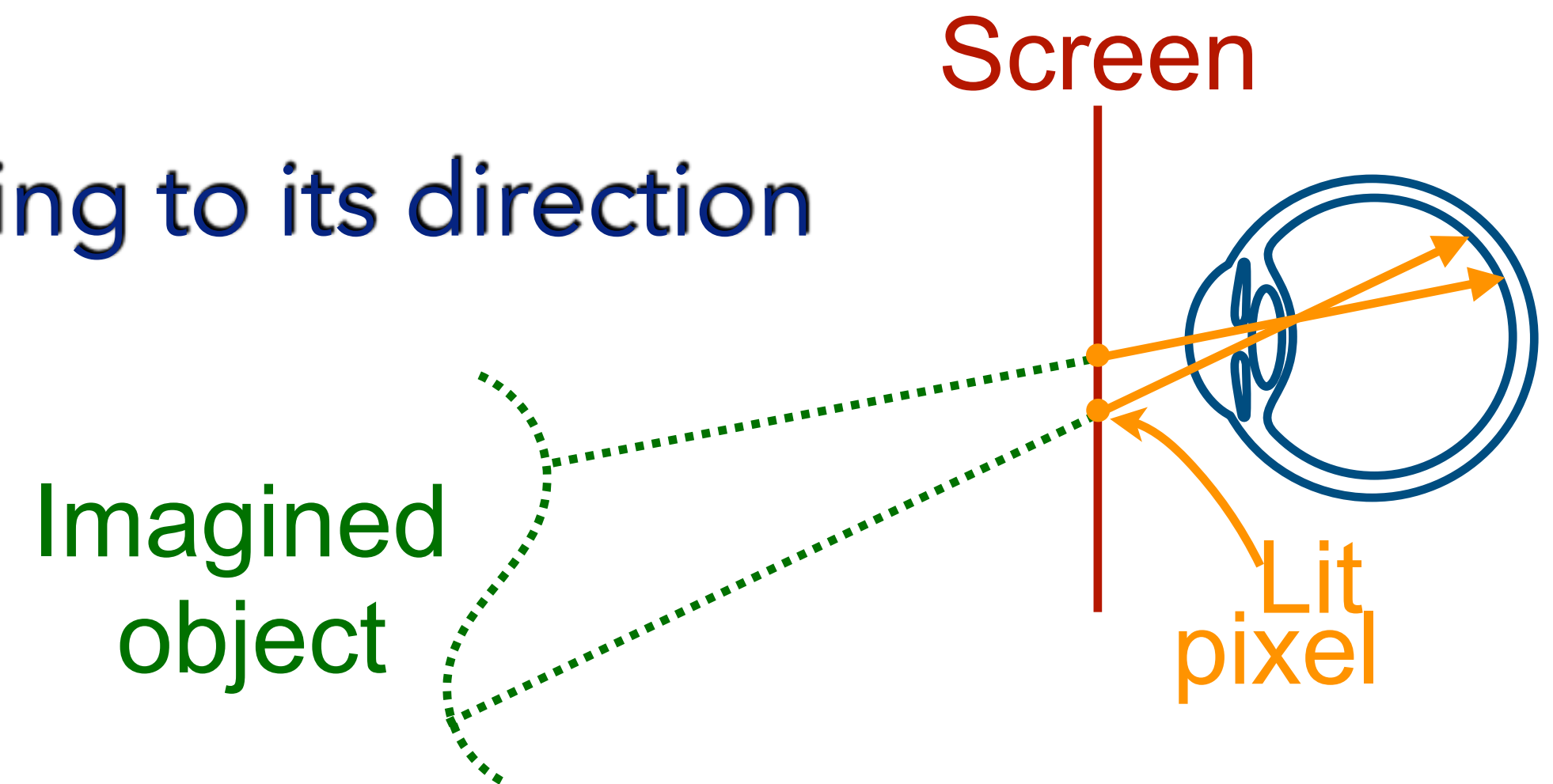
We will focus on monocular image formation
(for now)



Computer Monitor



- Light generator (pixel) on a grid
 - ➔ On a "Flat" surface (usually)
 - ➔ e.g., 2560x1664 pixels, ~224 pixels per inch
- "20/20" angular resolution is ~60 points per degree (~300 points at 1' distance)
- Each pixel must produce light corresponding to its direction

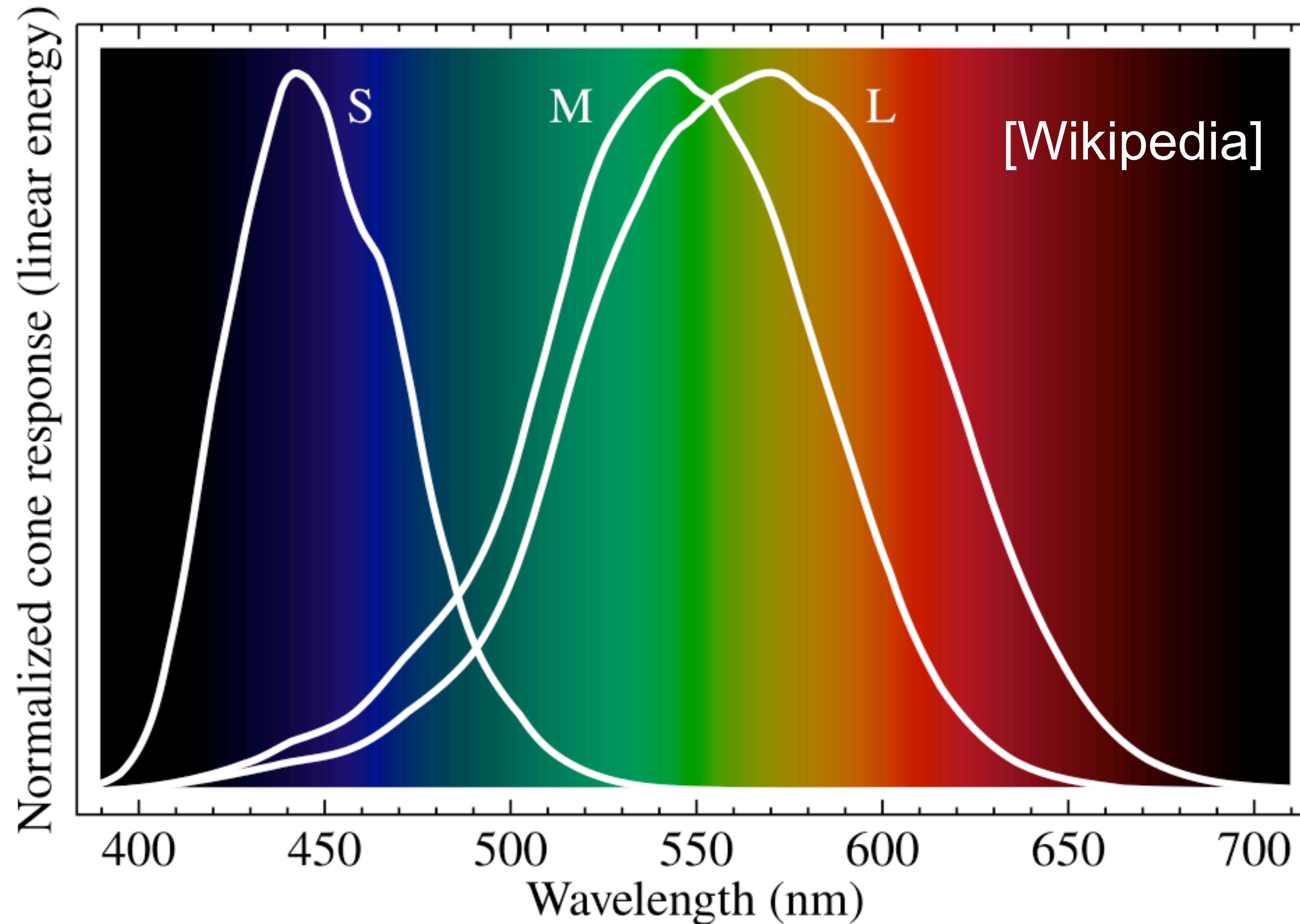


Light

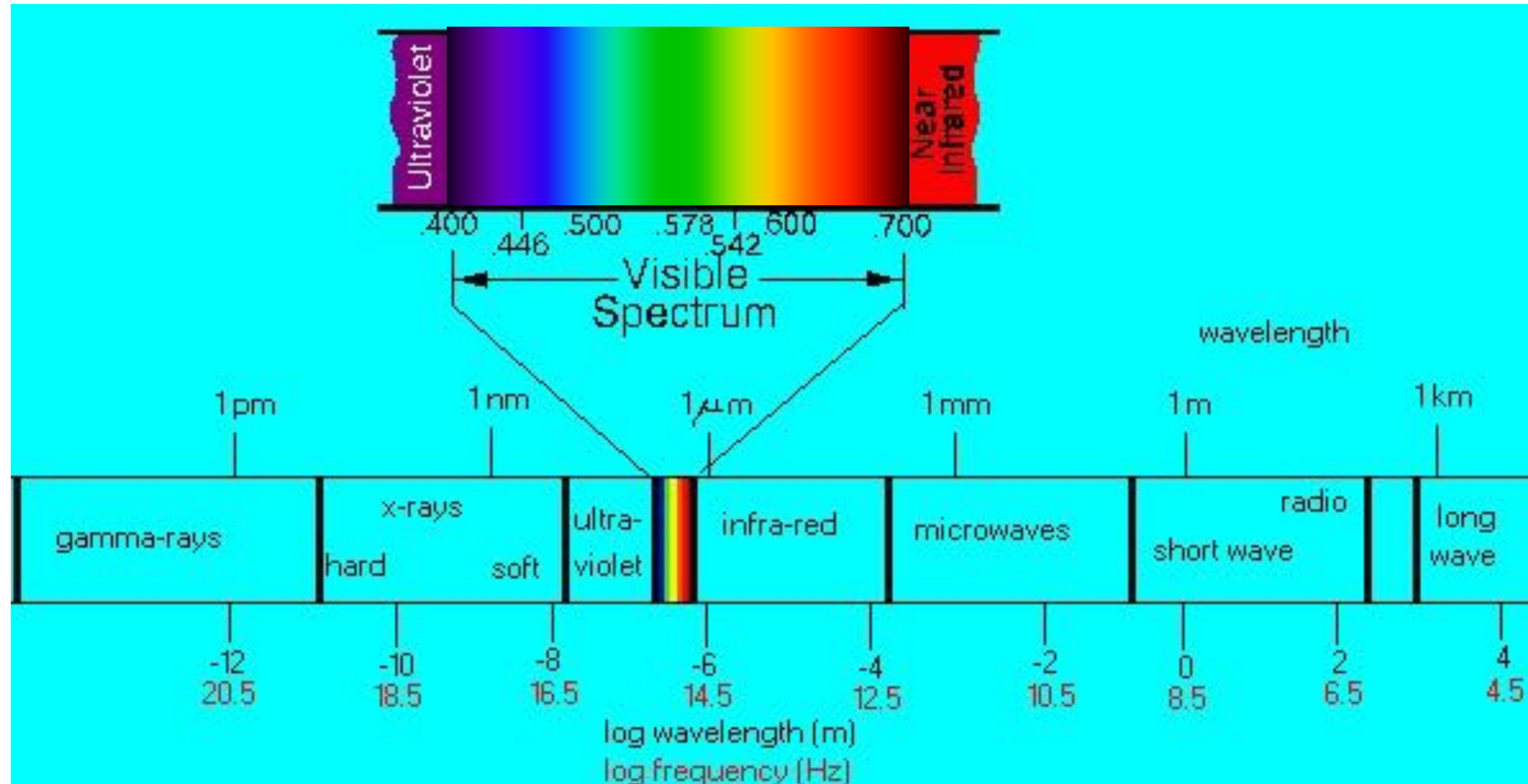


- Need to mathematically model light
 - ➡ Light $\neq$ R-G-B
- Electromagnetic energy
 - ➡ $h\nu == hc/\lambda$ (Joules)
 - ➡ c can vary with medium, λ can shift
- Perception of color is due to differing response of retina "cone" cells to λ values
 - ➡ Sensitivity to brightness is due to "Rod" cells

Cone Response Functions



Color Spectrum



Light



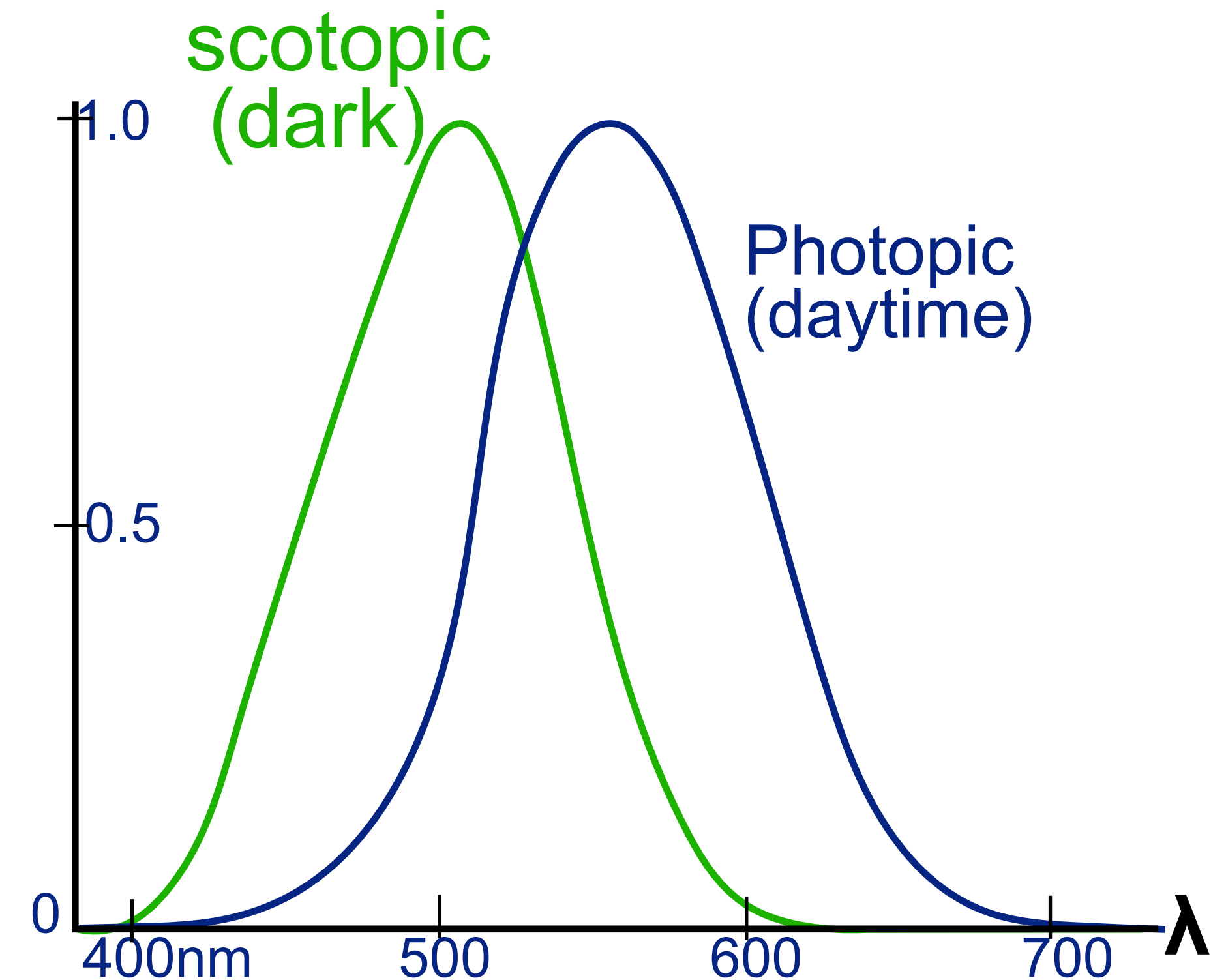
- Radiometry: EM energy measurement
 - ➔ Electromagnetic energy
 - ➔ $h\nu == hc/\lambda$ (Joules)
 - ➔ c can vary with medium, λ shifts
- Photometry: measurement of perceived brightness
 - ➔ weighed with luminous efficiency function

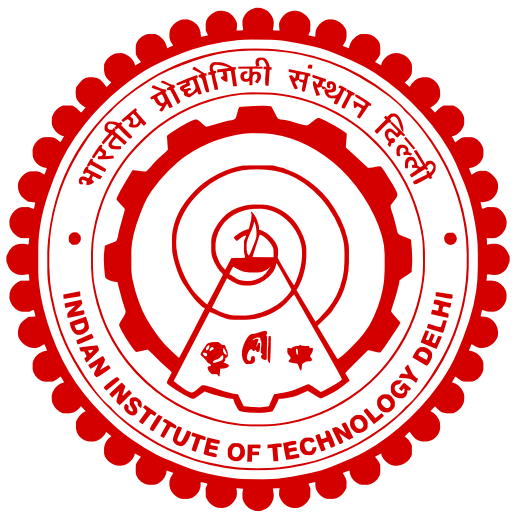




Luminous Efficiency

- Lumens per watt (lm/W)
- Bright light efficiency < 683 lm/W
 - ➔ @ Monochromatic light with $\lambda = 555$ nm
- Dark light efficiency < 1700 lm/W
 - ➔ @ $\lambda = 507$ nm





Radiometric Terms

- Spectral Energy (per unit wavelength) Q_λ
 - ➡ (Total Q due to interval $\Delta\lambda$)/ $\Delta\lambda \rightarrow dQ/d\lambda$ (unit: J/nm)
 - ➡ Total energy Q is Q_λ integrated over visible λ
- Irradiance, H_λ (light reaching a point p)
 - ➡ Spectral Power per unit area reaching a point on the surface $\phi_\lambda/\Delta A$: W/m²nm
- (Spectral) Radiance (light reaching point p from direction $-I$)
 - ➡ $H_\lambda/\Delta\sigma$, Irradiance per unit solid angle:
$$\frac{\Delta Q}{\Delta A \Delta \sigma \Delta t \Delta \lambda}$$



Surface Radiance

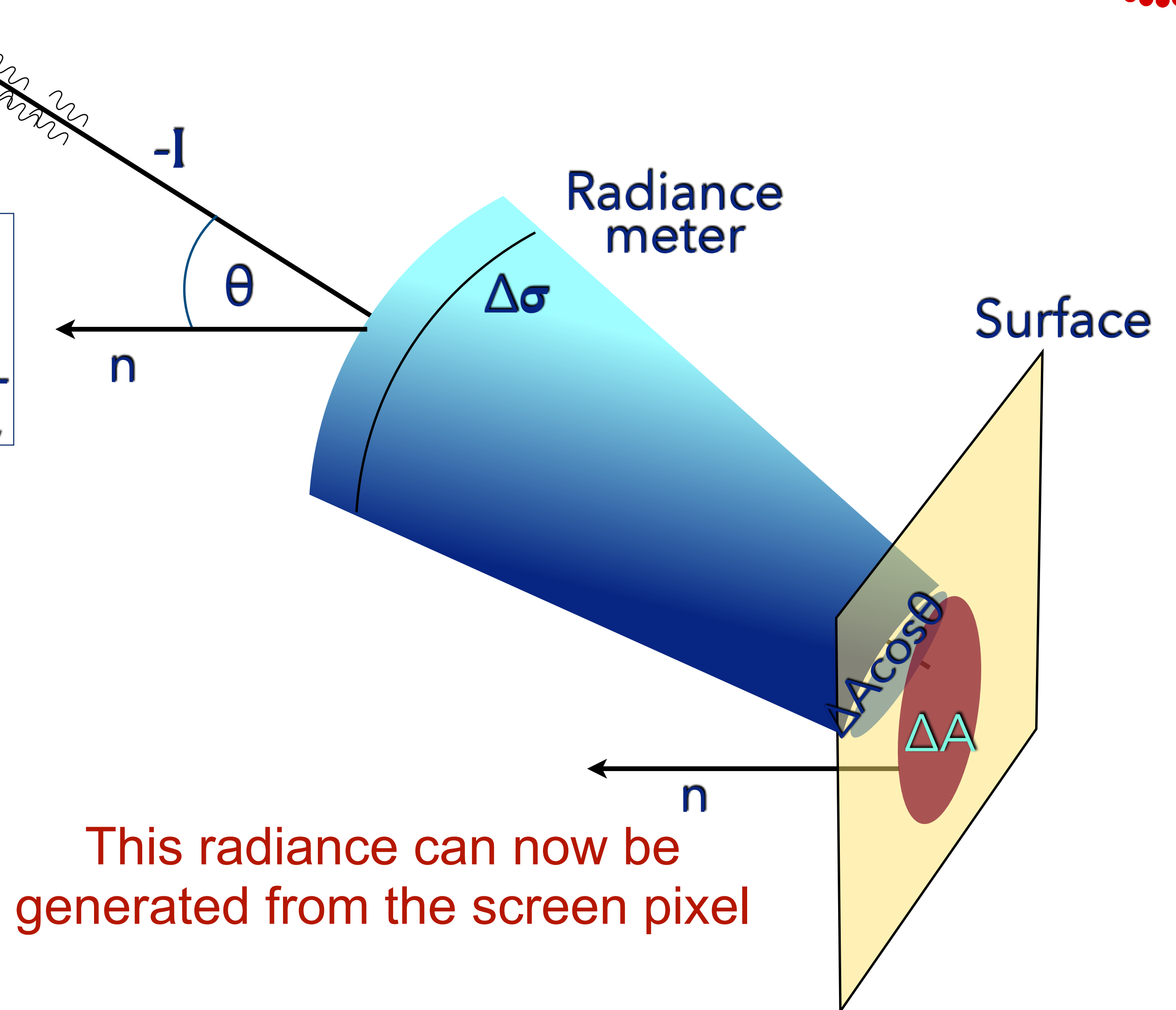
$$\text{(Spectral) Field Radiance } L_{f\lambda} = \frac{\Delta Q}{\Delta A \cos \theta \Delta \sigma \Delta t \Delta \lambda}$$

(from direction I)

$$\text{Irradiance } H_f = \int_{\text{(all incoming directions)}} L_f \cos \theta d\sigma$$

(dropping λ)

$$= \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi/2} L_f(\theta, \phi) \cos \theta \sin \theta d\theta d\phi$$





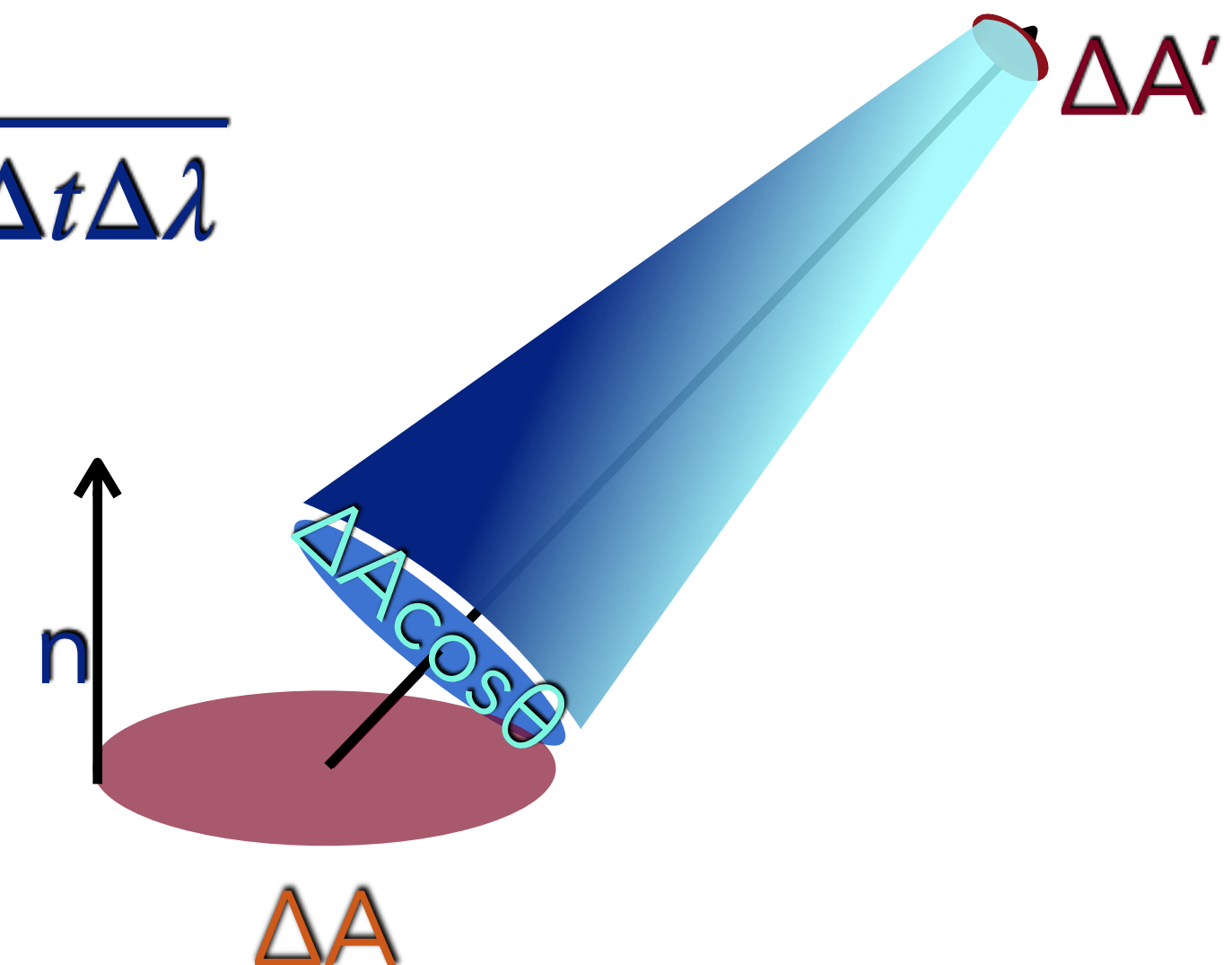
More Radiometric Terms

- Equivalent of Irradiance reflected from a surface is called radiant exitance, E

➔ Power per unit area leaving point p on the surface: $\frac{\Delta Q}{\Delta A \Delta t \Delta \lambda}$

- Surface radiance (light leaving point p in direction R), $L_s =$

➔ Radiant exitance per unit solid angle: $\frac{\Delta Q}{\Delta A \cos \theta \Delta \sigma \Delta t \Delta \lambda}$





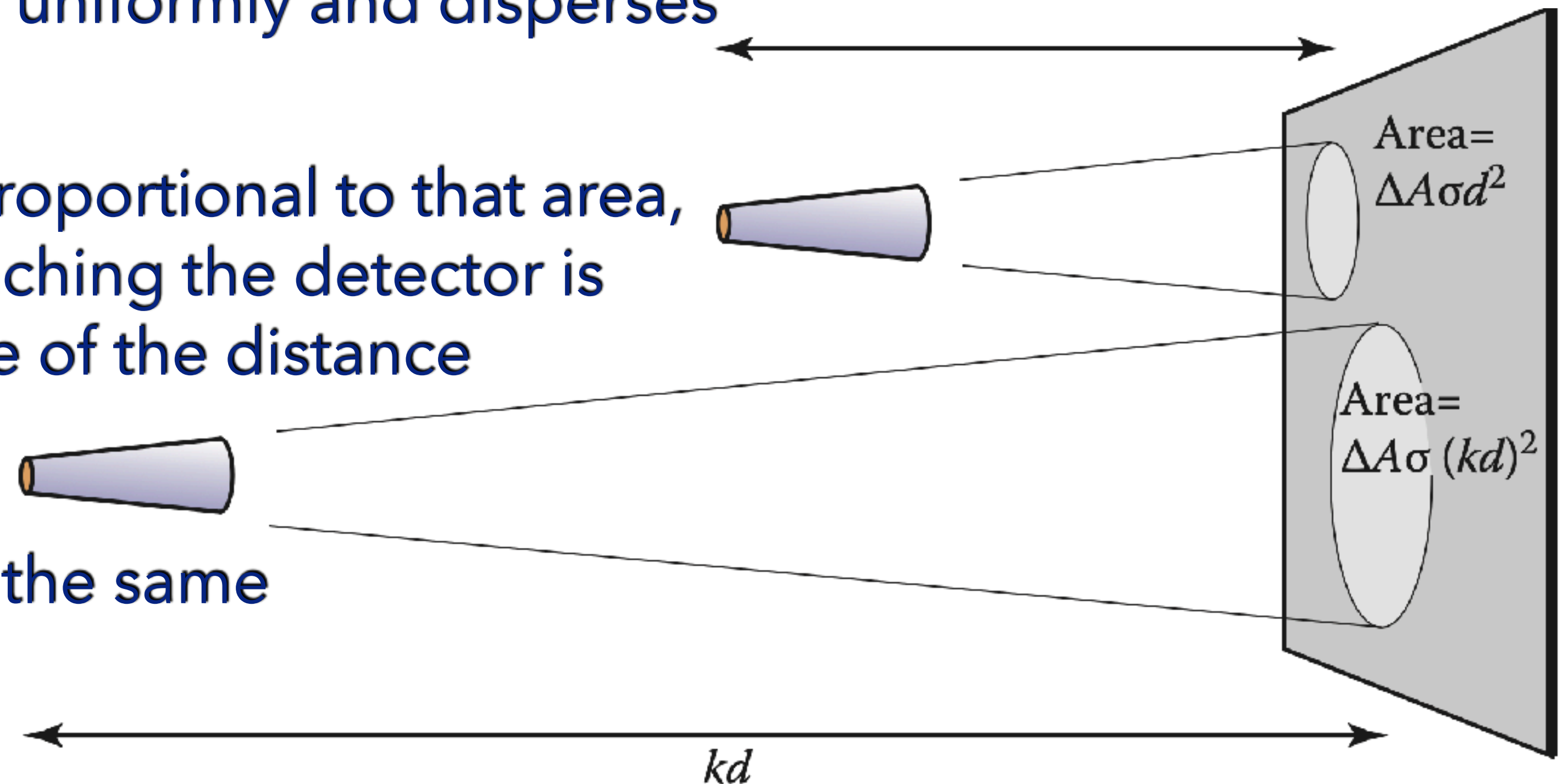
Invariance of Radiance

- (Spectral) Radiance is constant along an unobstructed line

- ➔ Assume power exits a surface uniformly and disperses uniformly in all directions

- ➔ ϕ_λ exiting the visible area is proportional to that area, and fraction of that power reaching the detector is proportional to inverse square of the distance

- ➔ ϕ_λ reaching both detectors is the same





Light Interaction

- Light can reflect, refract, diffract, scatter, polarize, interfere, be absorbed

➔ The most critical for computer graphics is reflection

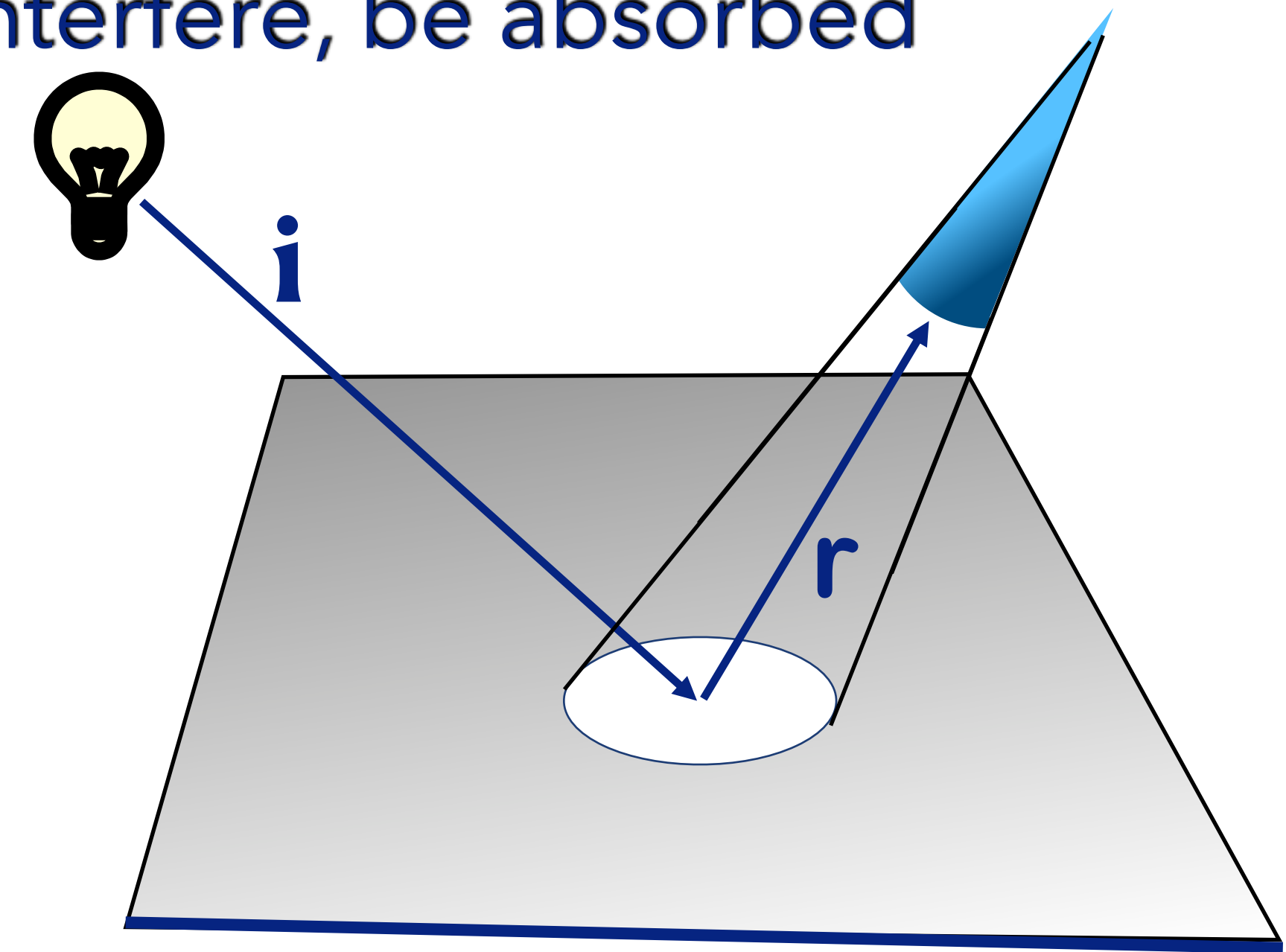
- ▶ Not just perfect mirror reflection
- ▶ Different photons from i may interact differently
- ▶ Macro-reflection is still symmetric

➔ Bi-directional Reflectance Function (BRDF, 4D)

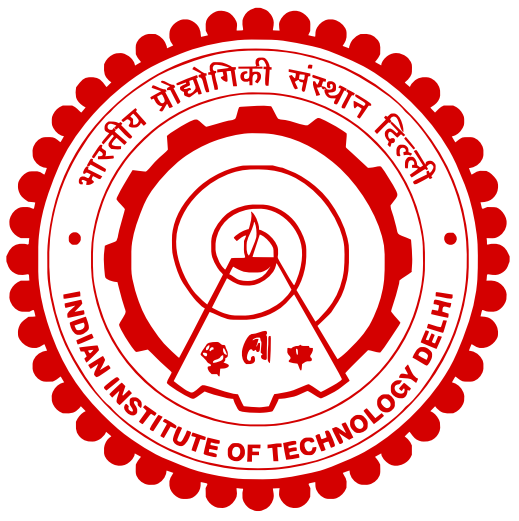
- ▶ $\rho_{ir} = L_r / H_i$

➔ Total Radiance for "pixel r "
(spectral)

$$= \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi/2} \rho_{ir} L_f(\theta, \phi) \cos \theta \sin \theta d\theta d\phi$$



Mostly, λ does not change



Types of BRDFs

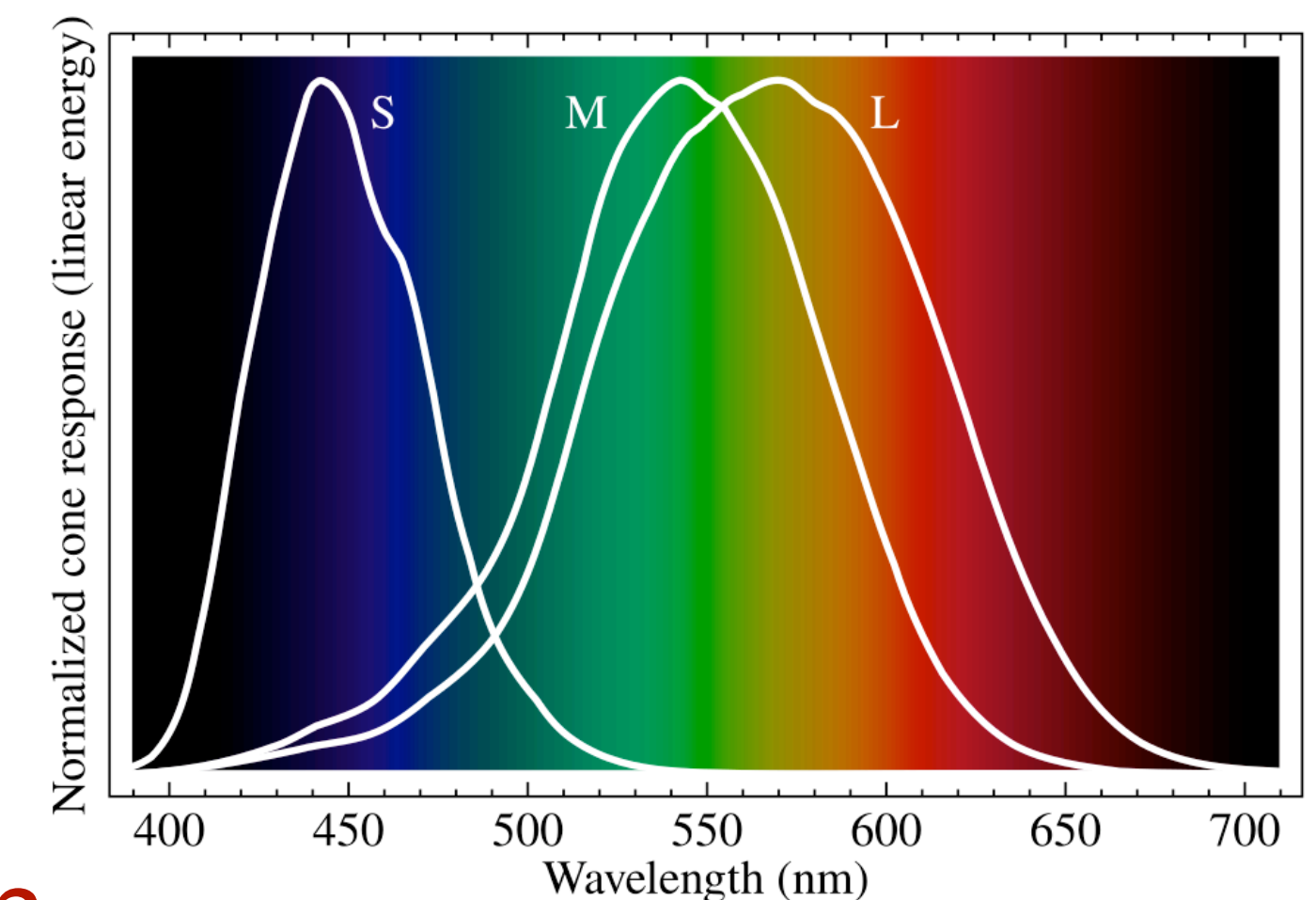
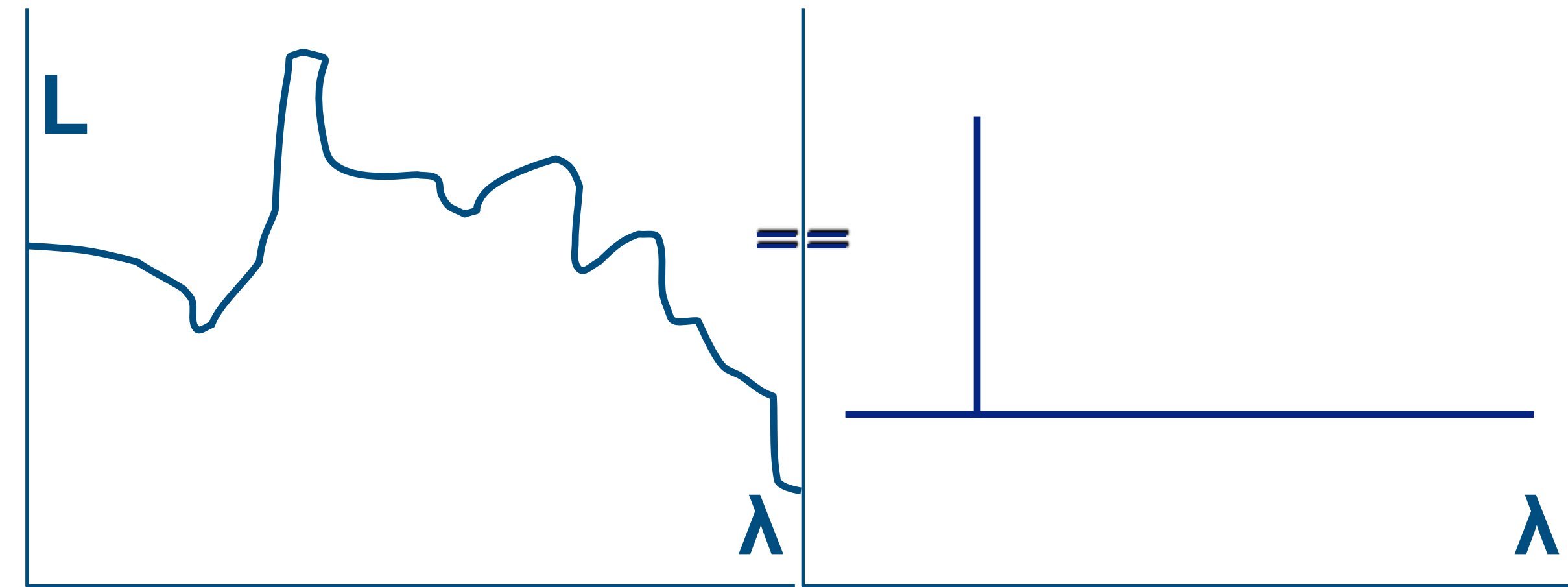
- Isotropic (independent of outgoing ϕ)
 - ➔ Reflectance independent of rotation about a given surface normal
 - ➔ Smooth plastics
 - ➔ Many independent of θ (reflect equally well in all directions)
- Anisotropic (Dependent on outgoing ϕ)
 - ➔ Reflectance changes with rotation around a given surface normal
 - ➔ Brushed metal, satin, hair





Tri-Stimulus Theory

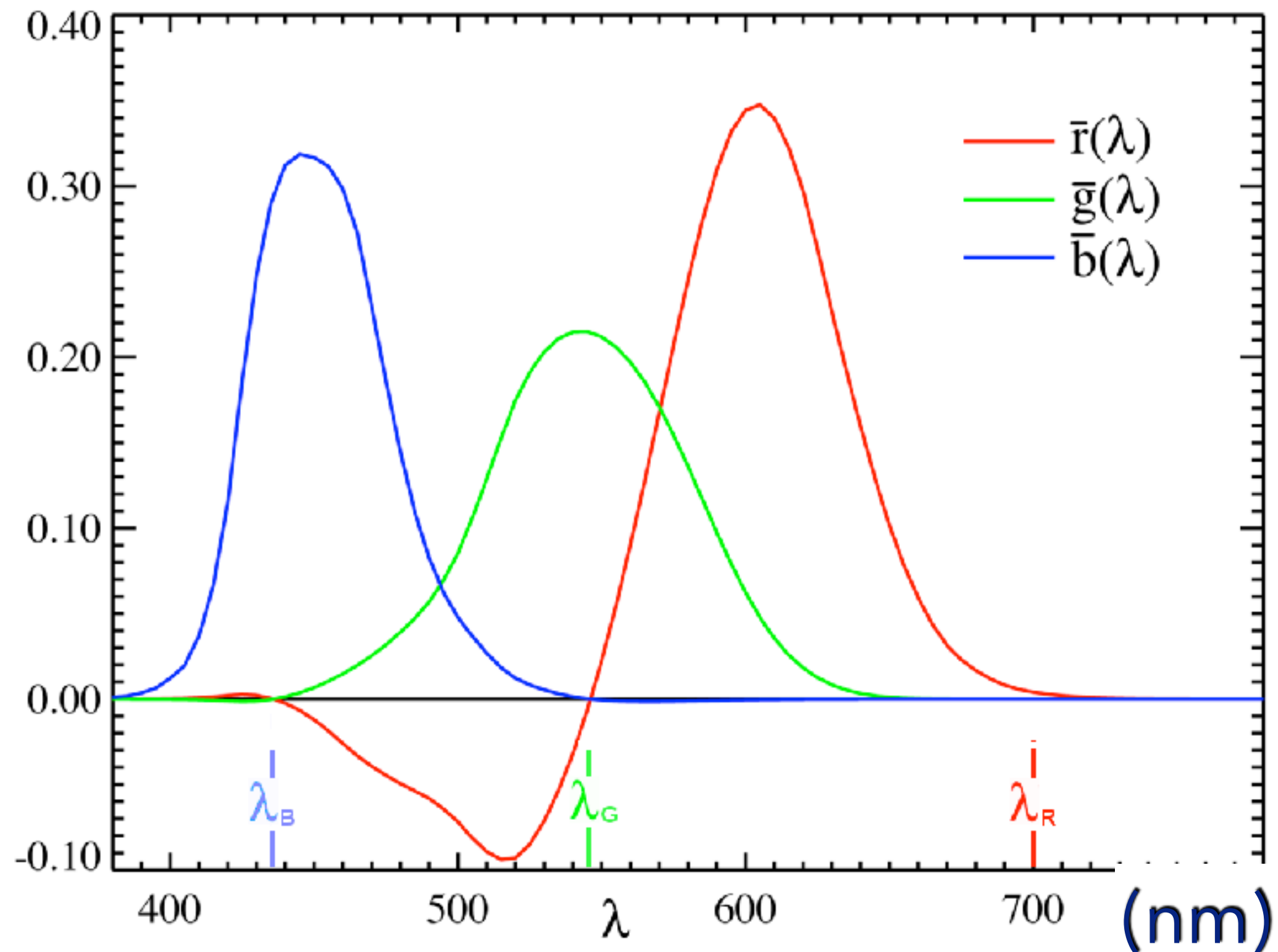
- Metamers appear the same
- Retina has photosensors:
 - ➔ Rods (low resolution, Peripheral, Many)
 - ➔ Cones (High res, in fovea, few, 3 types)
 - ▶ Maximum response at 420 nm (blue),
 - ▶ Maximum response at 534 nm (Bluish-Green),
 - ▶ Maximum response at 564 nm (Yellowish-Green).
- ➔ Integrating (Filtering) Sensors



Tri-stimulus theory: 3 values can describe every visible color perception

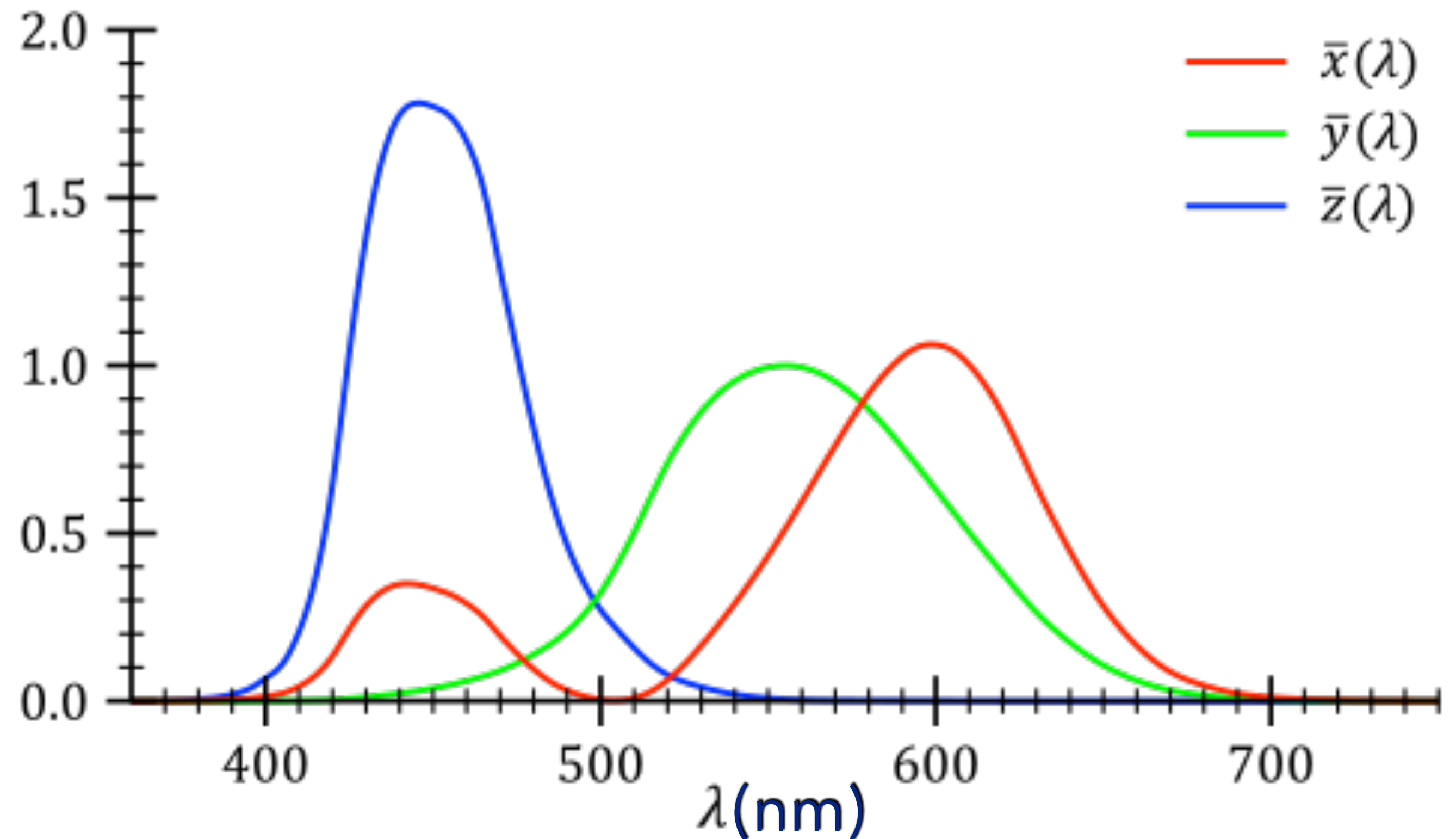


Color Matching



Primaries: 435.8, 546.1, 700 nm

$$\text{Spectrum} = R \overline{r(\lambda)} + G \overline{g(\lambda)} + B \overline{b(\lambda)}$$



Imagined Primaries s.t. $\bar{y}$ has the luminance response function, and $\bar{x}$ and $\bar{z}$ remain +ve

$$= X \overline{x(\lambda)} + Y \overline{y(\lambda)} + Z \overline{z(\lambda)}$$



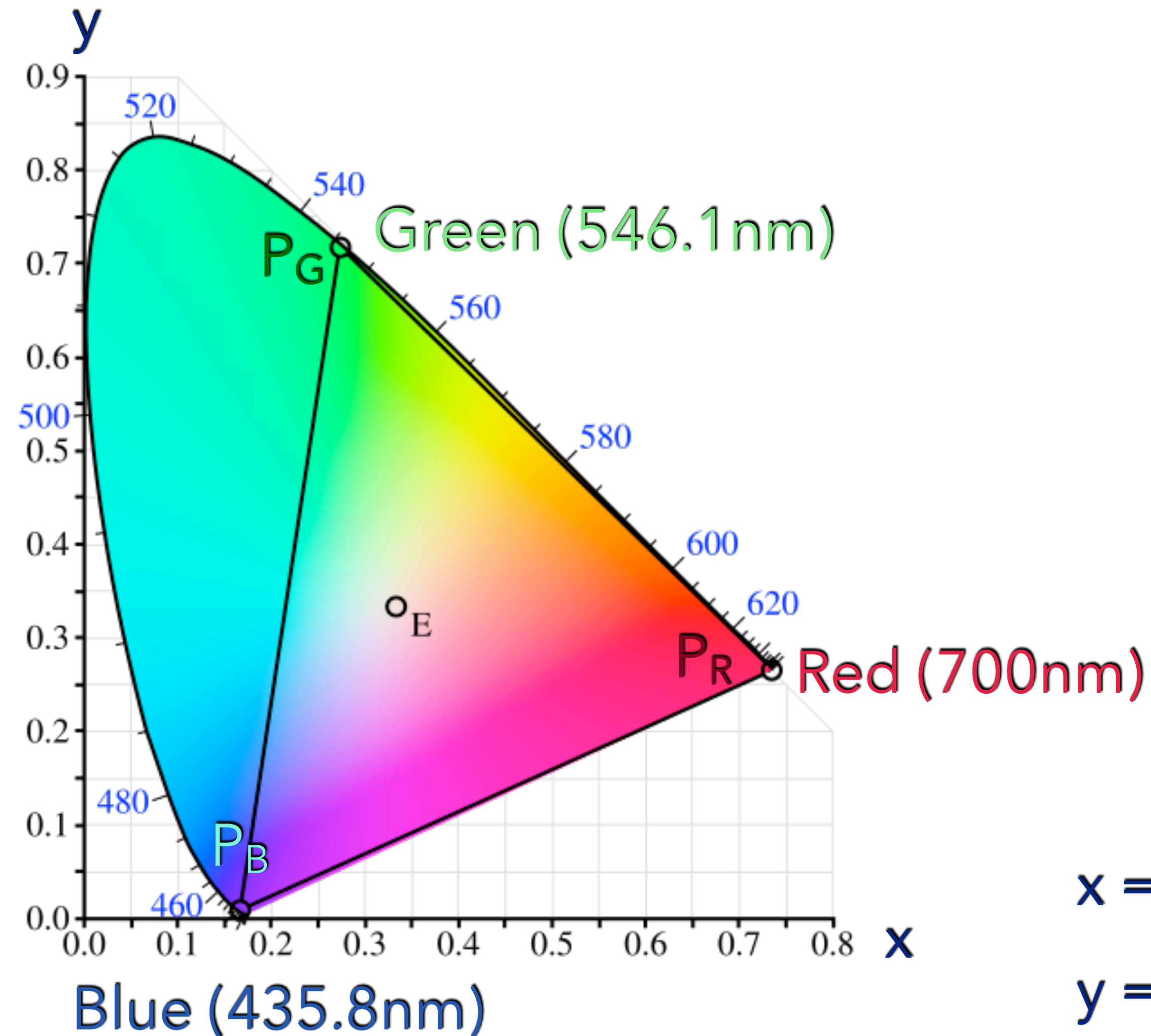
Color Transformation

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \frac{1}{0.17697} \begin{bmatrix} 0.49 & 0.31 & .20 \\ 0.17697 & 0.8124 & 0.01063 \\ 0 & .01 & .99 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Linear Transformation



CIE Chromaticity Diagram



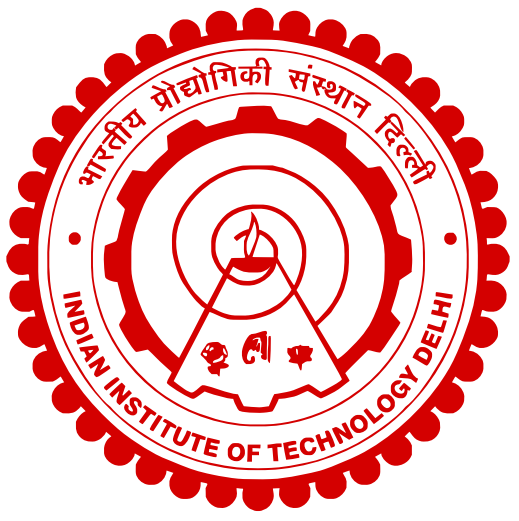
$$R P_R + G P_G + B P_B$$

is a point within the triangle
 $P_R P_G P_B$ for $0 \leq R, G, B \leq 1$

Any color gamut can now
be shown on this diagram

$$x = X/(X+Y+Z)$$

$$y = Y/(X+Y+Z)$$



Color Spaces

- XYZ
- HSV
- RGB
 - ➔ Different R G B primaries in use
- sRGB
- Lab
- CMYK
- HDR

Color Spaces

- XYZ

- HSV

- RGB

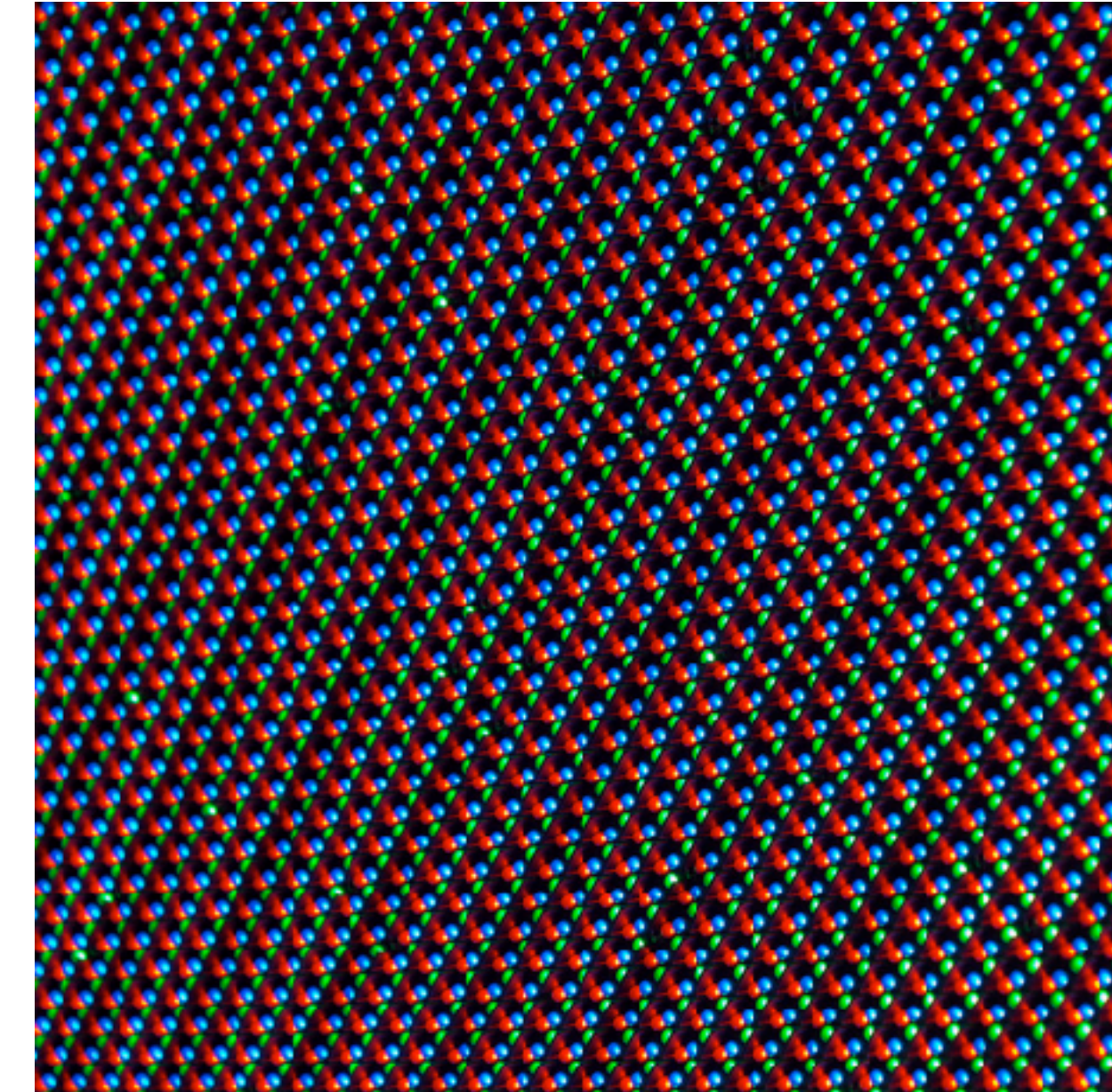
➔ Different R G B primaries in use

- sRGB

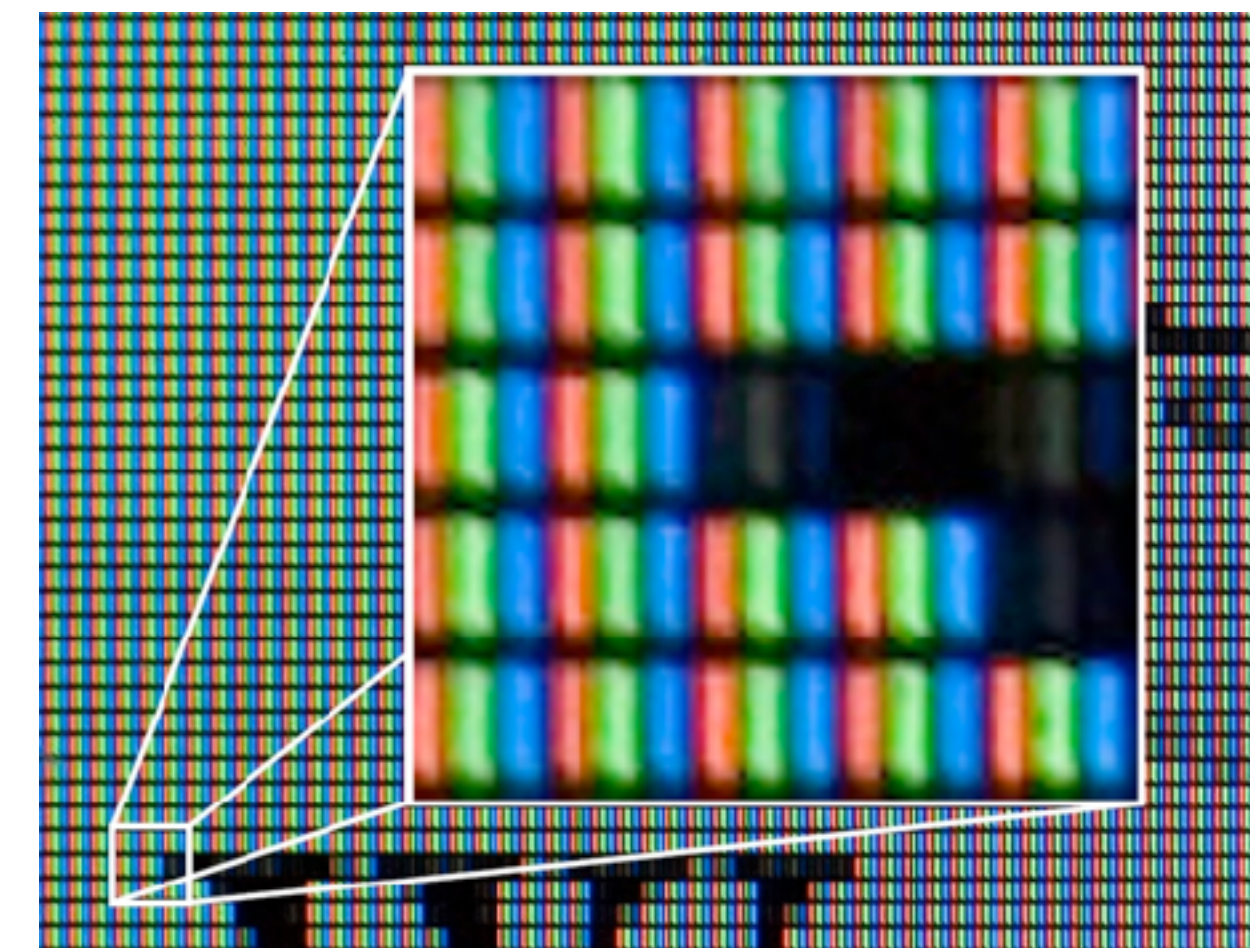
- Lab

- CMYK

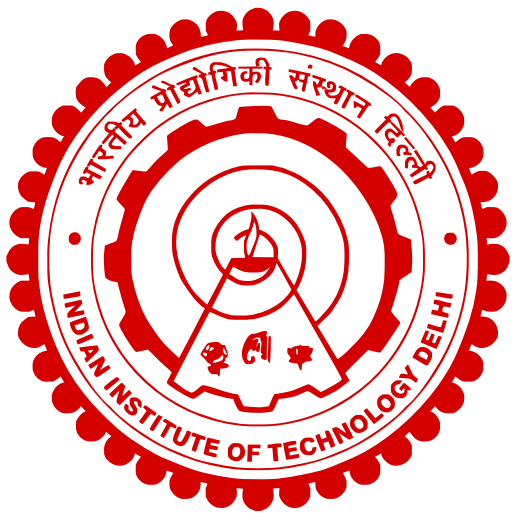
- HDR



LED
display



LCD
display



Displayed Color

- The gamut differs across monitors
 - ➔ Different white points, varies ambience, knob controls, even age
- We do not store color or radiance in SI units but in a normalized range 0..1
 - ➔ 1 translates to maximum brightness supported by monitor, 0 to minimum
- What about the intermediate values? 0.5?
 - ➔ Midway radiance (SI units) or midway intensity producible by the monitor?
 - ➔ More complication: we can distinguish differences in low luminance better
- How do monitor use these values? Control a voltage? Pulse width modulation?
 - ➔ Historically, the monitor intensity did not increase linearly with controlling voltage

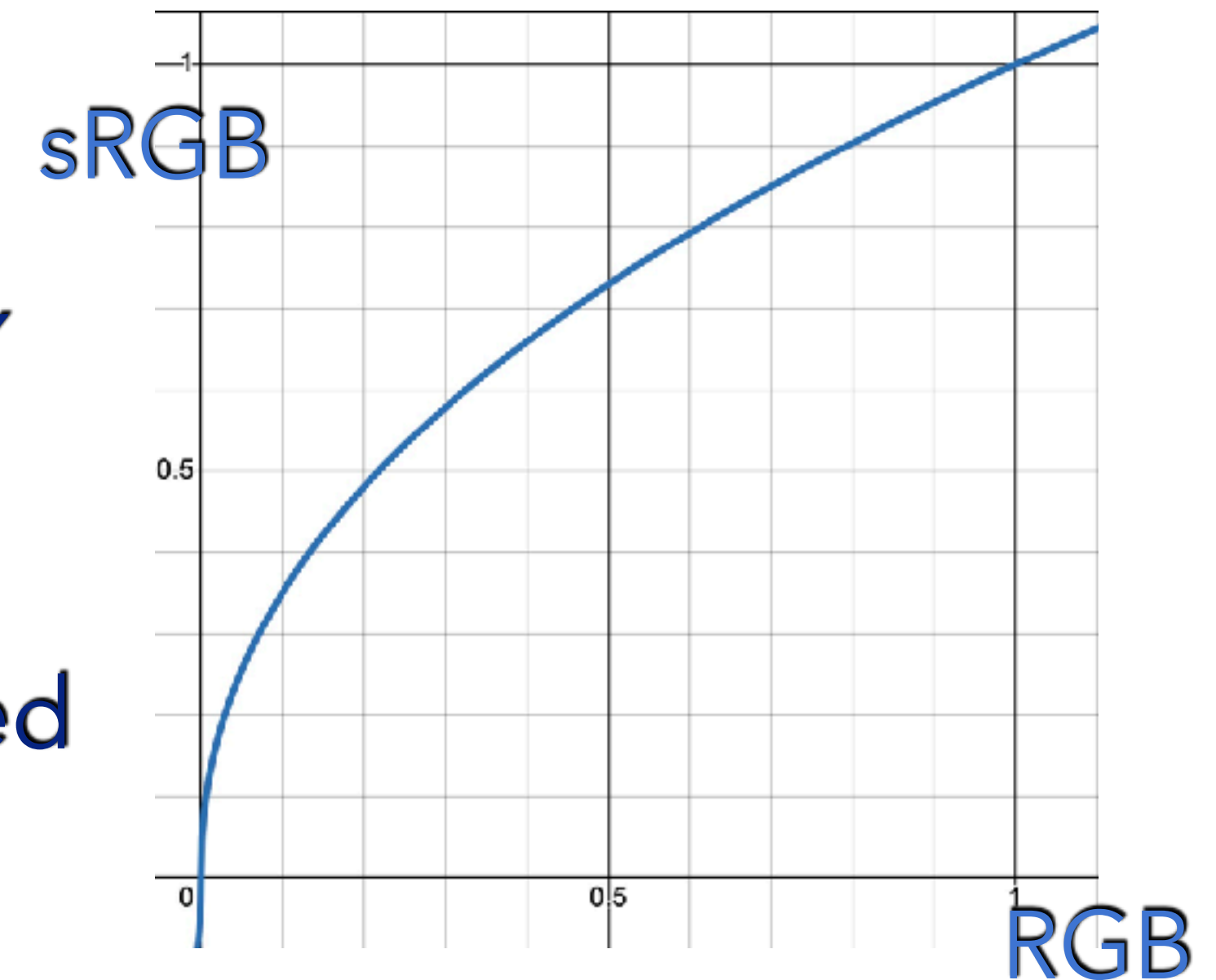
Linear $\neq$ Perceptually uniform



Gamma Correction



- Say, (sub)pixel's range is $0..1$, and digitized into 2^b levels (e.g., using b bits, $b = 8$)
 - ➔ Values are $0, 1/255, 2/255, \dots, 1$
 - ➔ How should the monitor use these values?
- For value v , $\text{displayed_intensity} = \text{Maximum_Intensity} * v^\gamma$
 - ➔ Typical value of γ : 2.2
- To allow the intensities' perception to be uniformly spaced
 - ➔ Send $v^{1/\gamma}$ instead of v to the monitor
 - ➔ Images may already be quantized in 'gamma-corrected' space

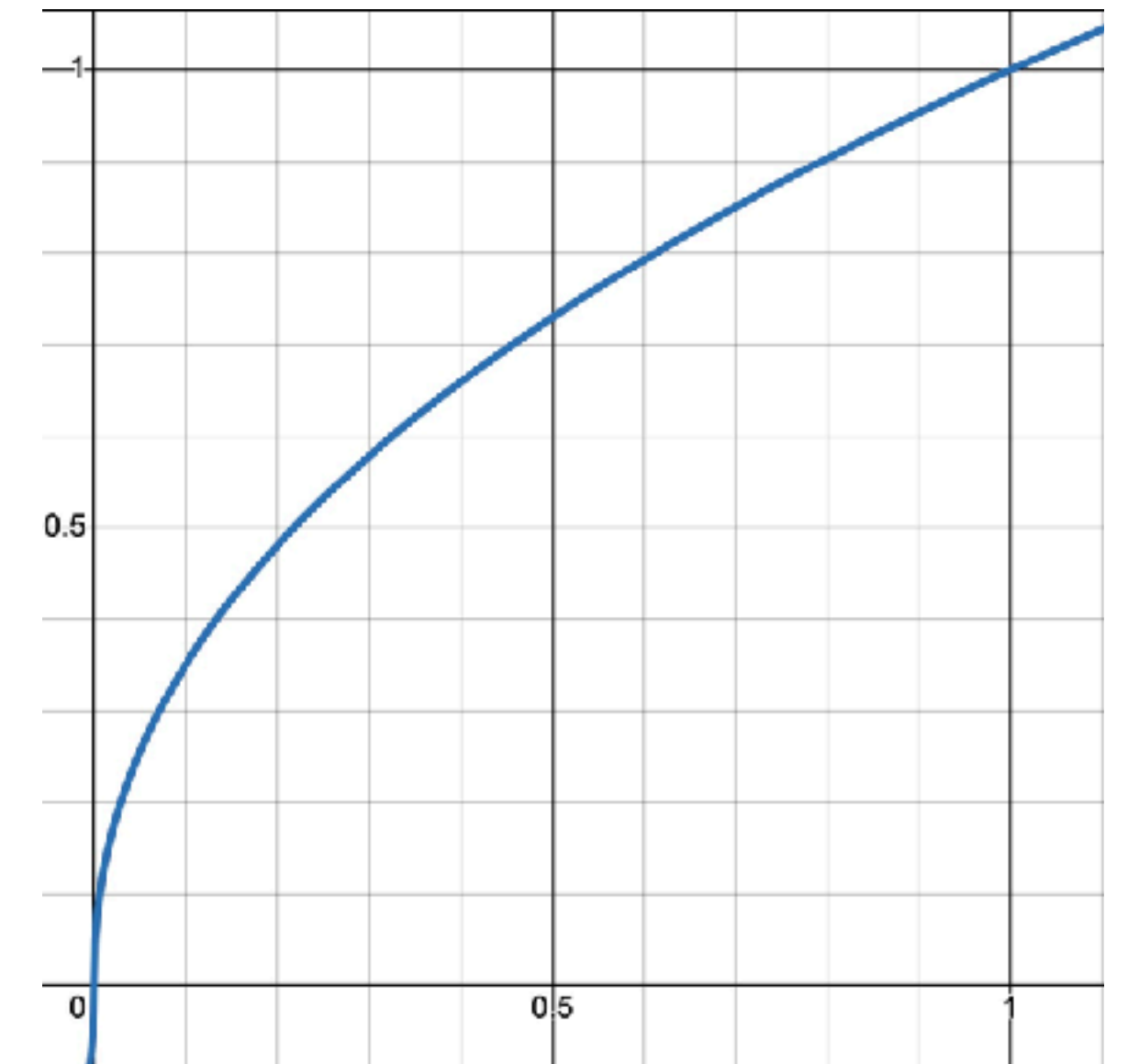


Linear vs Gamma Scale

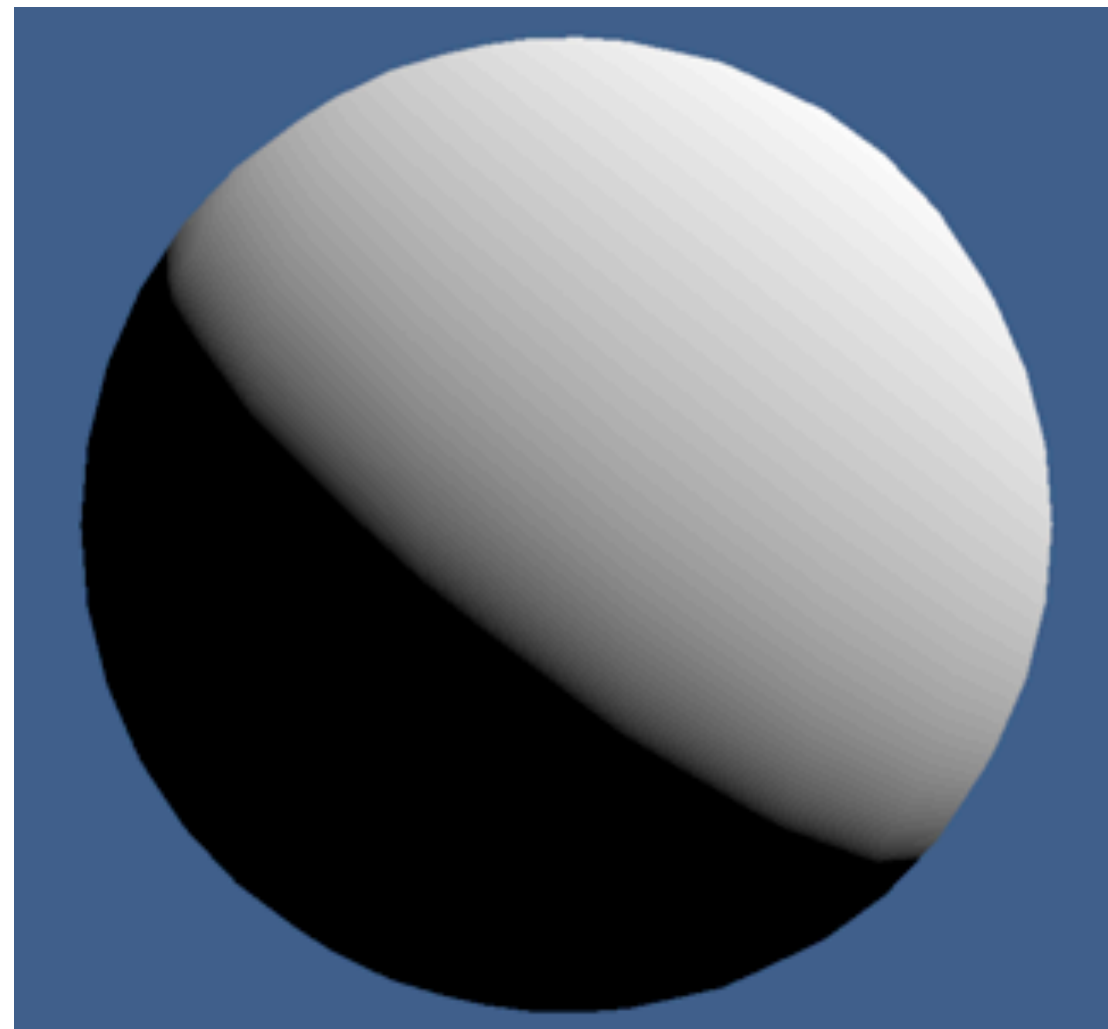


Without Gamma Correction

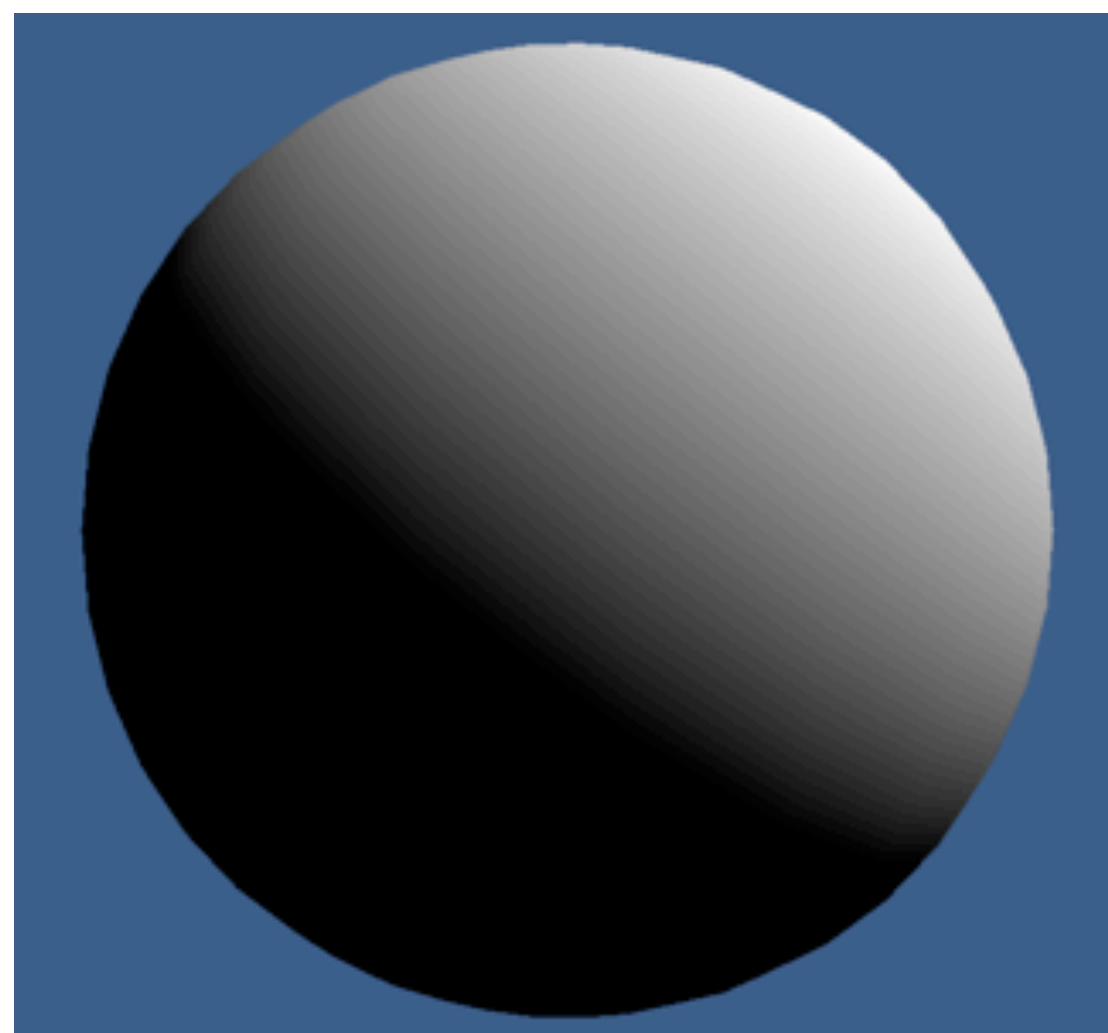
Gamma Corrected



Linear vs Gamma Encoded



Linear Space



Gamma Space

