Week 8

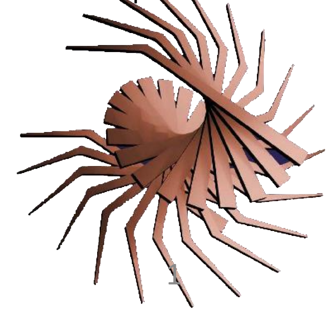
Light Emitters 1

OLED Basics

Quantifying Efficiency for Displays and Lighting

Chapter 6.1 – 6.3

Concepts in Organic Electronics
Stephen R. Forrest



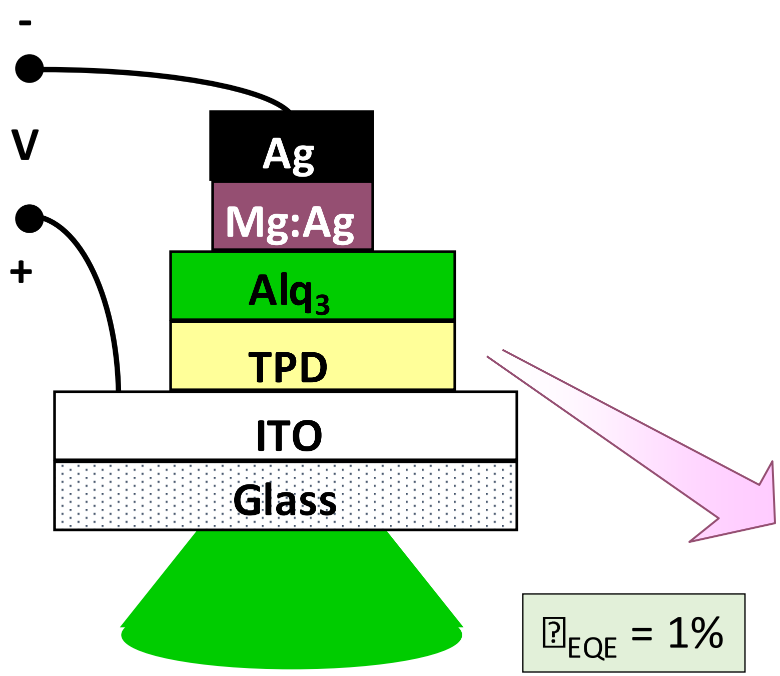
Objectives

- Learn about vision: what makes a good display or lighting fixture?
- Gain a knowledge of how fundamental properties of organics leads to arguably the most important organic electronic device: OLEDs
- Learn about challenges yet to be met before OLEDs completely dominate the display market
- Learn about the challenges for lighting

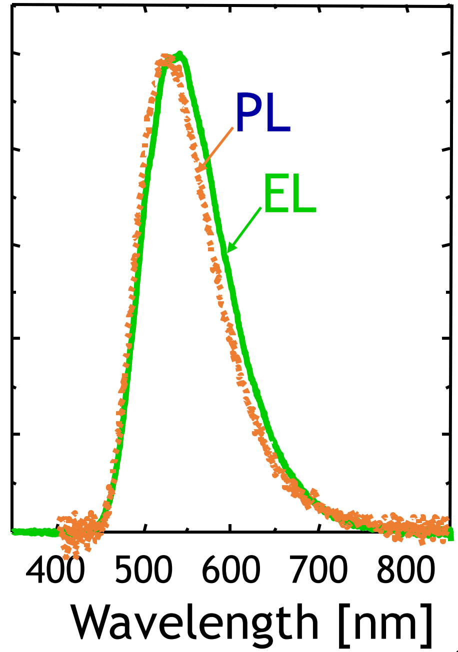
OLEDs

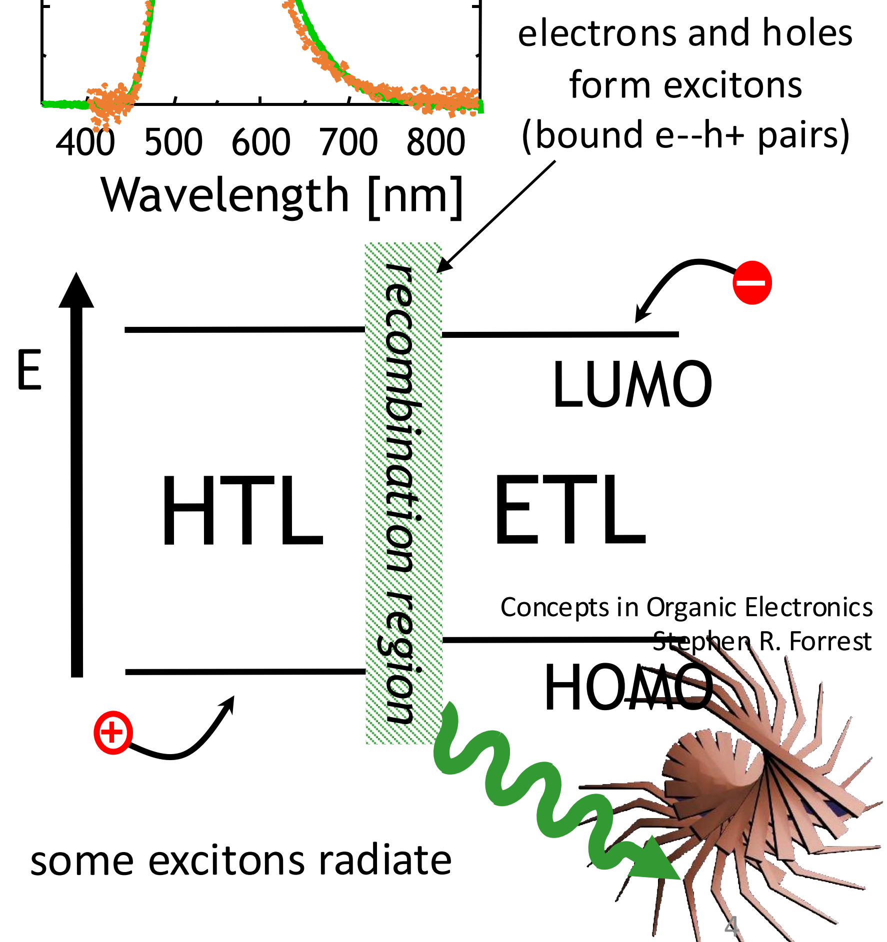
- Basic concepts
- Displays and Lighting
  - R-G-B pixelation
  - WOLEDs
  - TOLEDs
- Getting light out
- Intensity roll-off and annihilation
- Device reliability

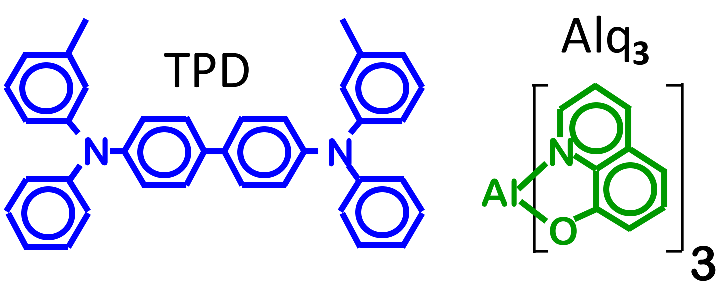
Organic Light Emitting Diode (OLED)



η_{EQE} = 1%







Tang & van Slyke, Appl. Phys. Lett., **51**, 913 (1987)

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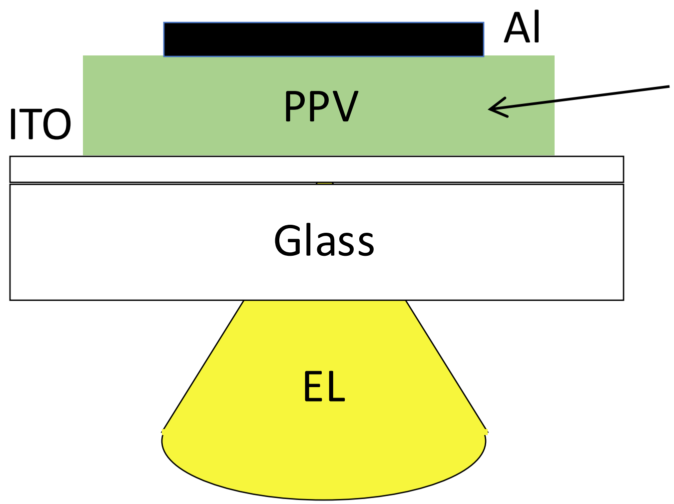
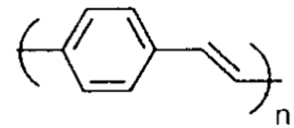
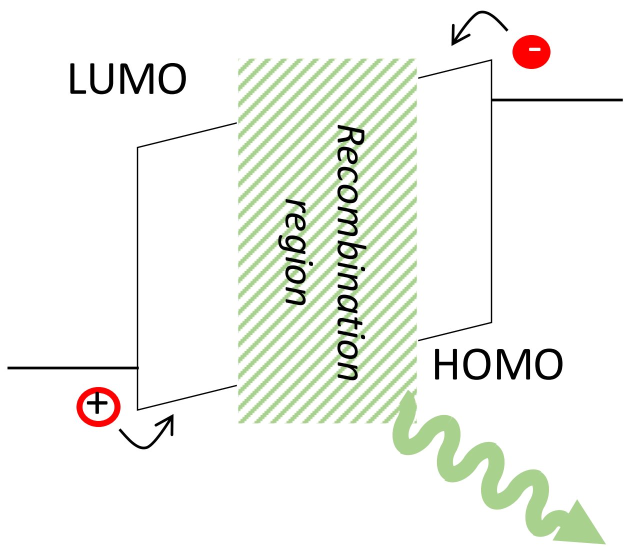
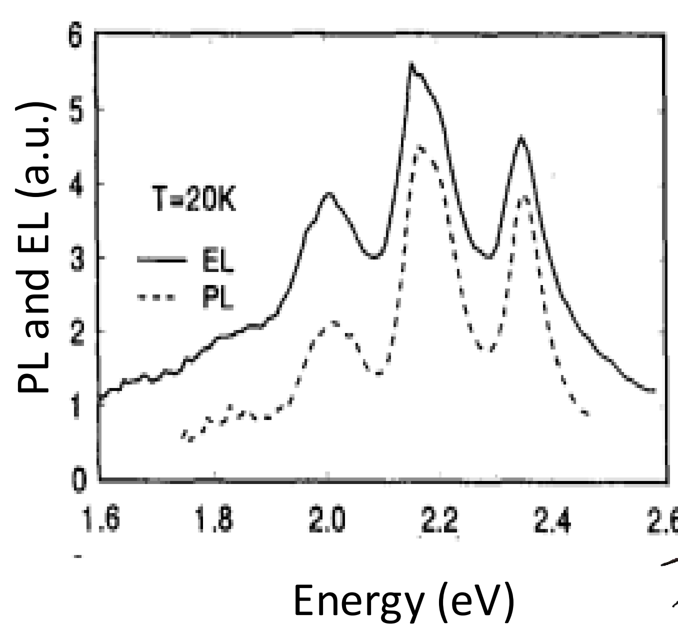
First Polymer OLED





$\eta_{EQE} = 0.1\%$

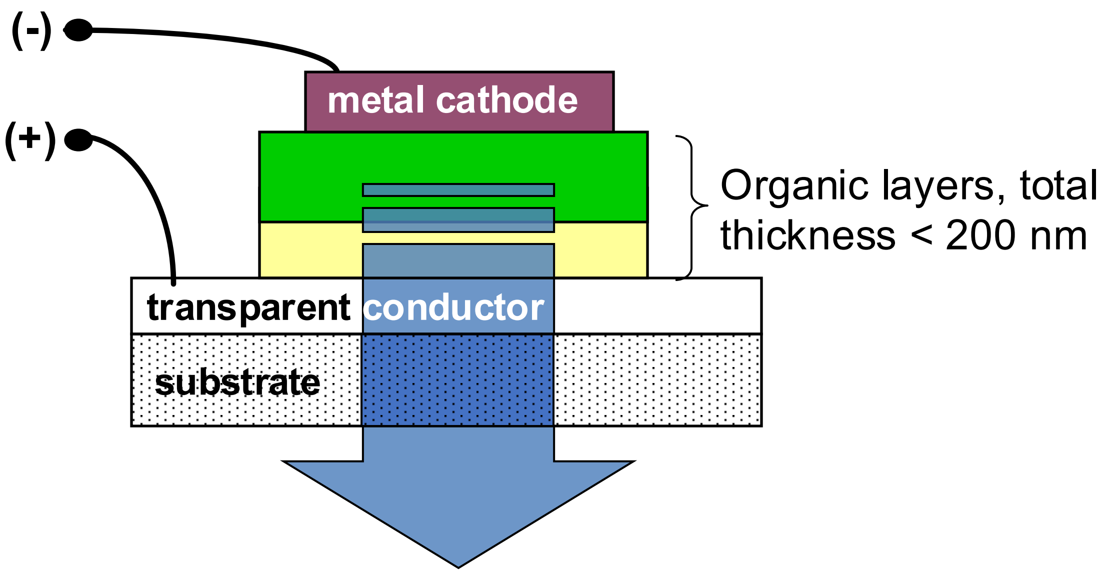




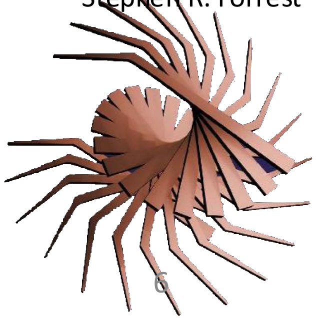
Recombination zone not well-defined

Burroughes, et al. *Nature,* **347,** 539 (1990).

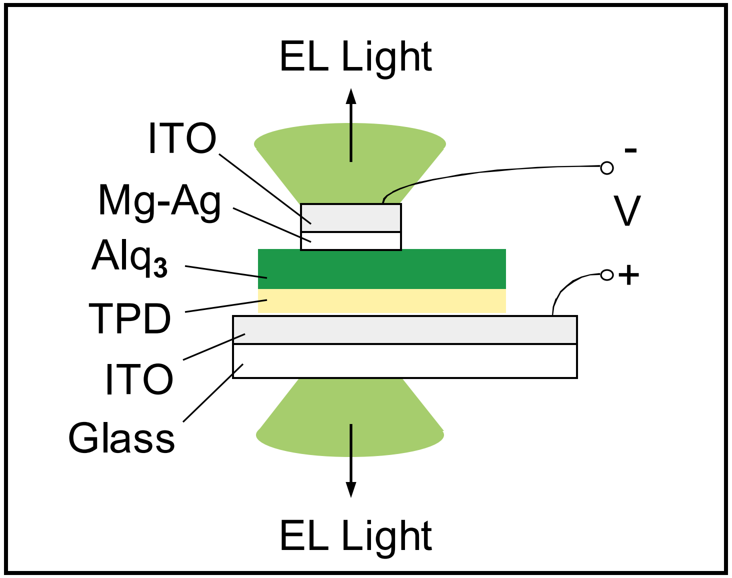
Benefits of OLEDs



- Can be prepared on any substrate - active materials are amorphous
- Low cost materials and fabrication methods, scalable to large area
- Readily tuned color and electronic properties *via* chemistry
- Can be transparent when off
- Device characteristics
  - Efficiency ~ 100% demonstrated, white > 150 lm/W
  - > 1,000,000 hour (100 years) lifetime
  - Can be very bright: 10^6 cd/m^2, CRT = 100 cd/m^2, fluorescent panel = 800 cd/m^2
  - Turn-on voltages as low as 3 V



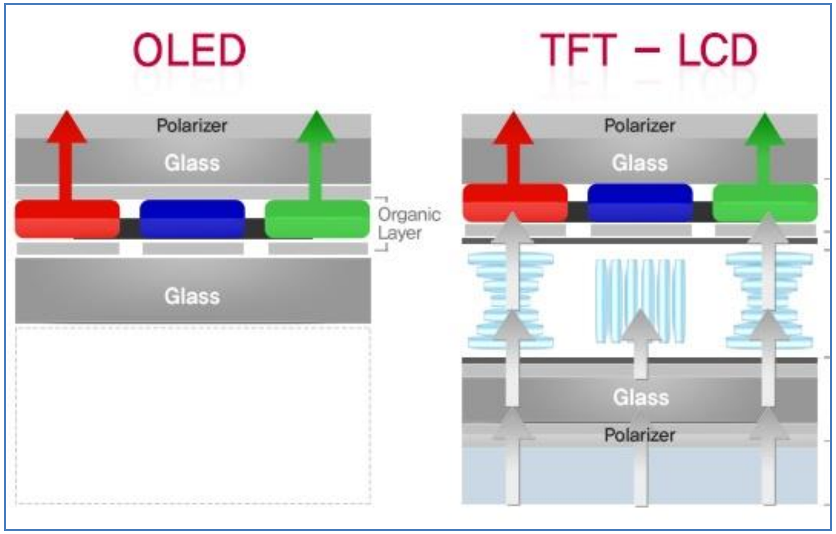
Transparent OLED (TOLED)



- Devices can be > 90% transparent
- Thin metal or electron injection layer is capped with ITO
- Transparent cathode can also be used to prepare top emitting structures
  - OLEDs on metal sheets
  - OLEDs on Si backplanes in AMOLED displays

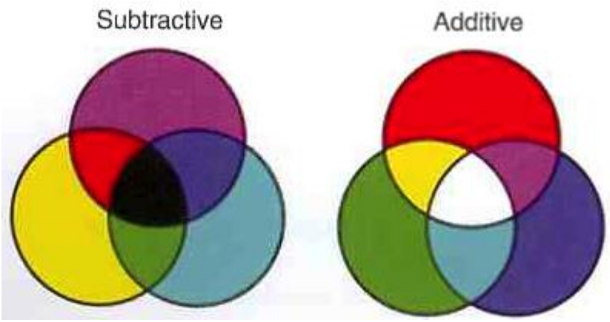
Bulovic, V., et al. Nature, **380**, 29 (1996).

OLED vs. Liquid Crystal Displays (LCDs)



Display Technologies

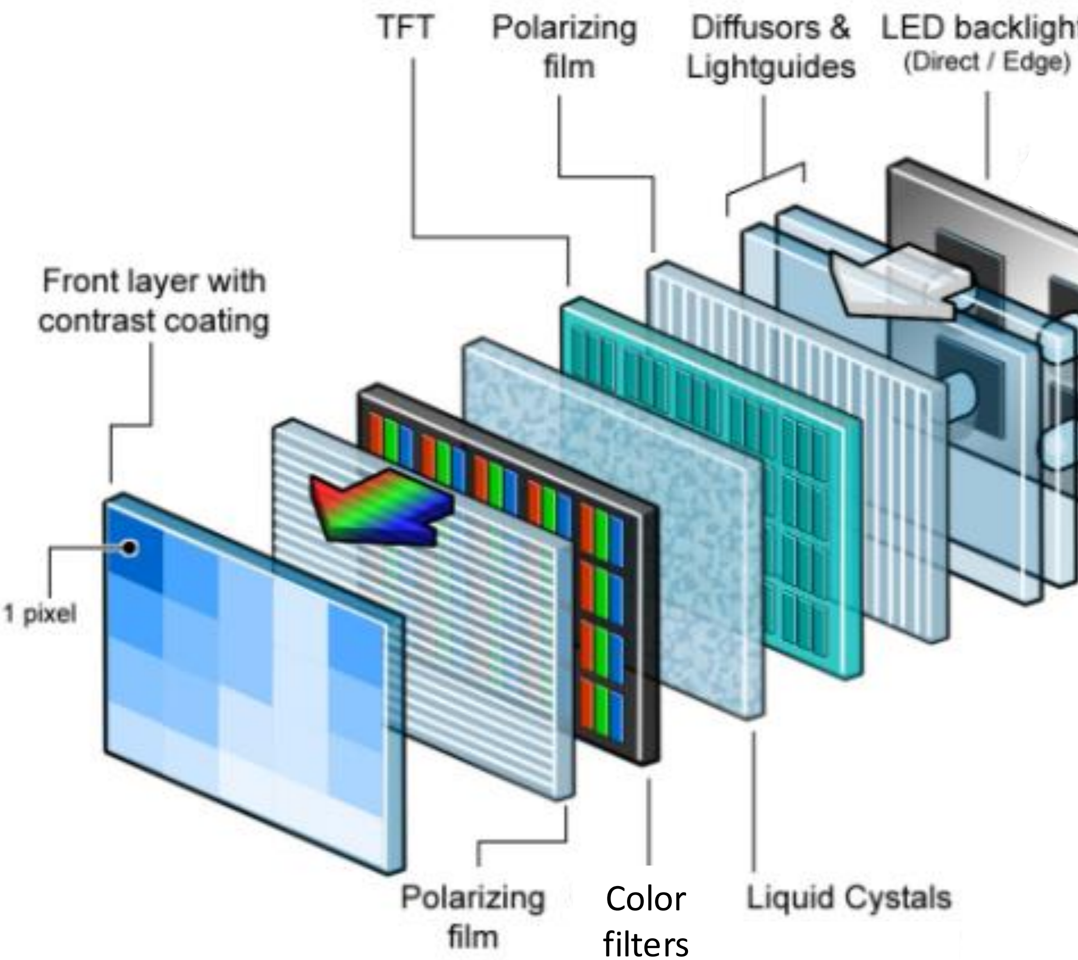
Color Mixing

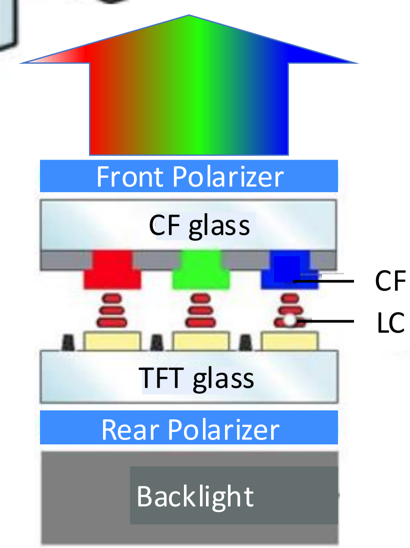


LCD

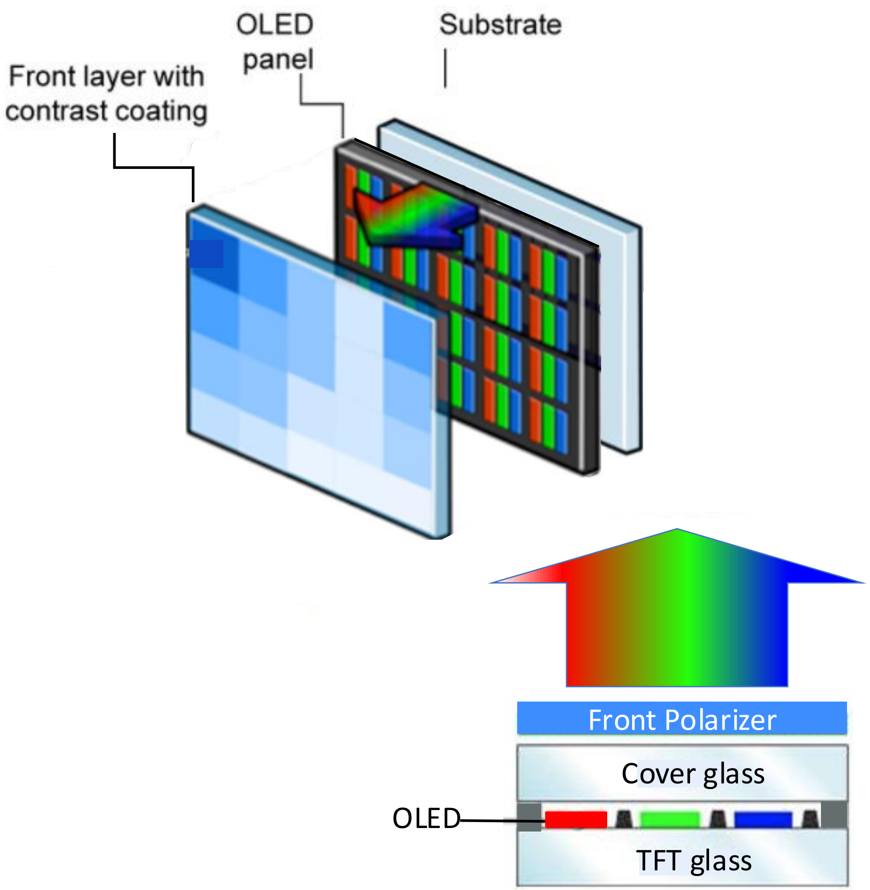
OLED
Plasma
CRT

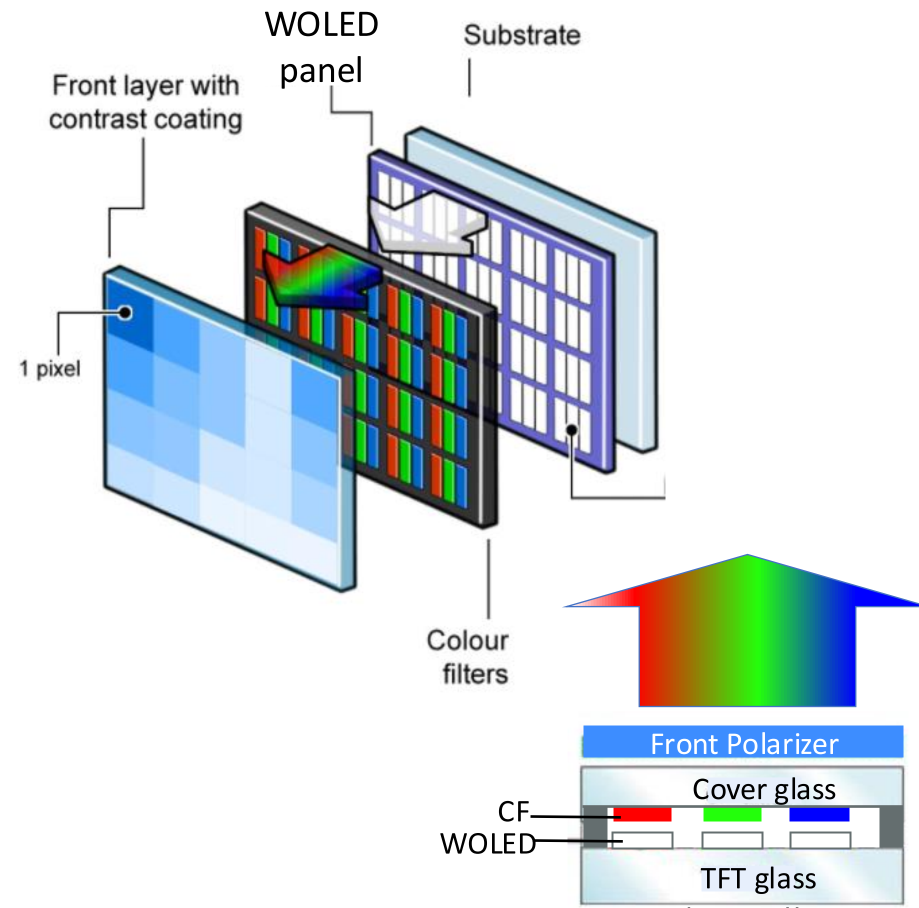
LCD/LED Displays





Two Types of OLED Displays





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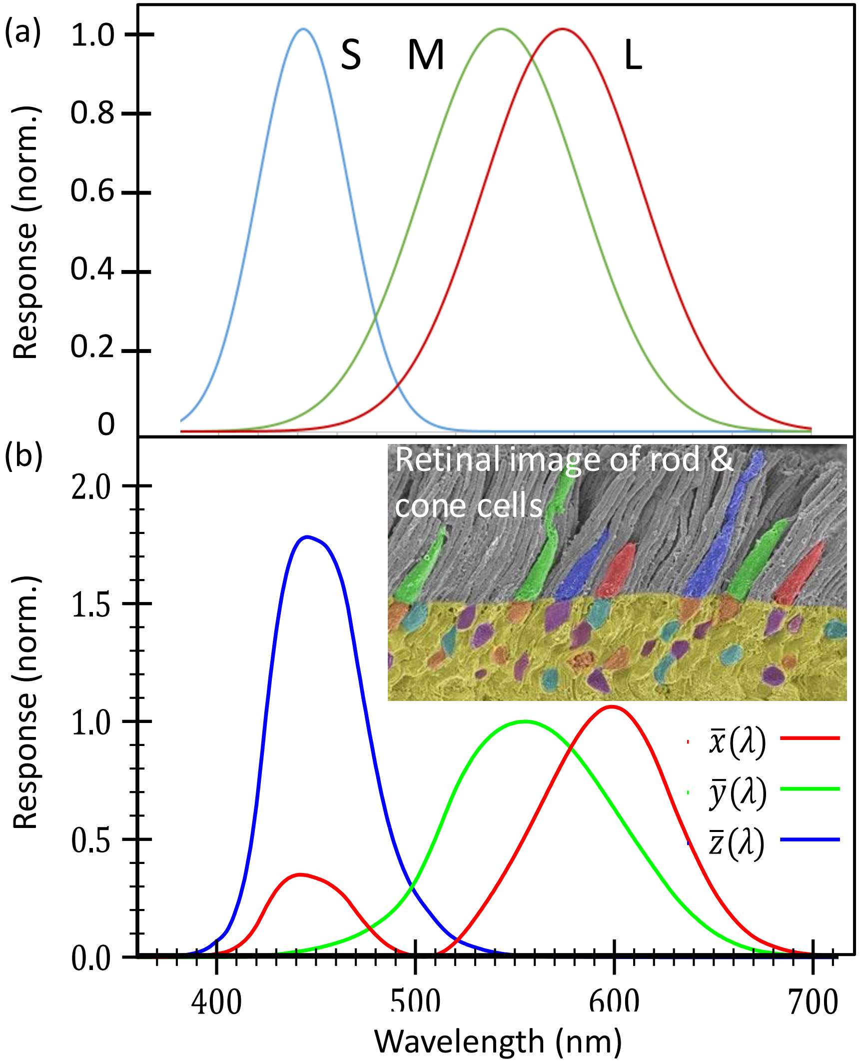
- RGB pixels
- Top emitting
- Dominates mobile (Samsung)

- WOLED pixels + Color filters
- Top emitting
- Dominates TVs (LG)

How We See Color: Tri-Stimulus Curves and Chromaticity



Cone cell response

color matching functions

Tri-stimulus values

$$X = \int I(\lambda)\bar{x}(\lambda)d\lambda$$

$$Y = \int I(\lambda)\bar{y}(\lambda)d\lambda$$

$$Z = \int I(\lambda)\bar{z}(\lambda)d\lambda$$

$I(\lambda)$=un-normalized spectral intensity

CIE Coordinates

$$x = \frac{X}{X+Y+Z}; \quad y = \frac{Y}{X+Y+Z}; \quad z = \frac{Z}{X+Y+Z}$$

s
t

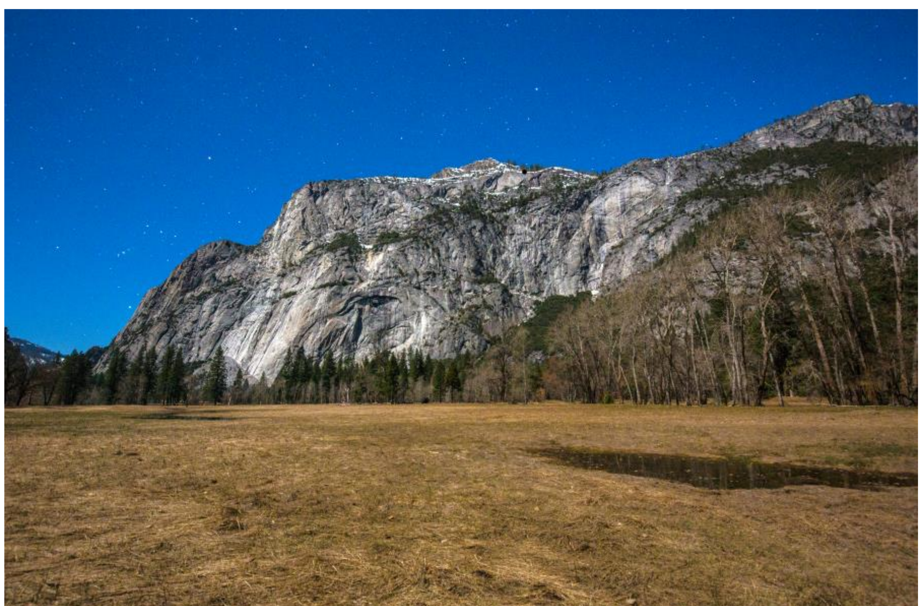
$$x + y + z = 1 \quad \Rightarrow \quad z = 1 - x - y$$

Scotopic vs. Photopic Vision Response

How things appear at night

Scotopic vision due to the rod cells
– only sense luminosity (brightness) but not color

(simulation)

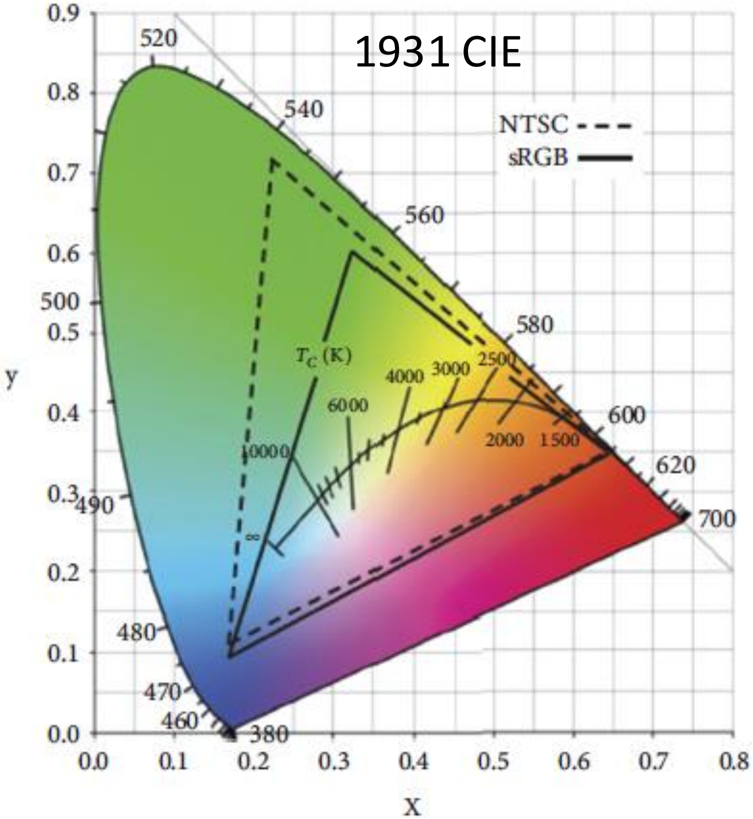


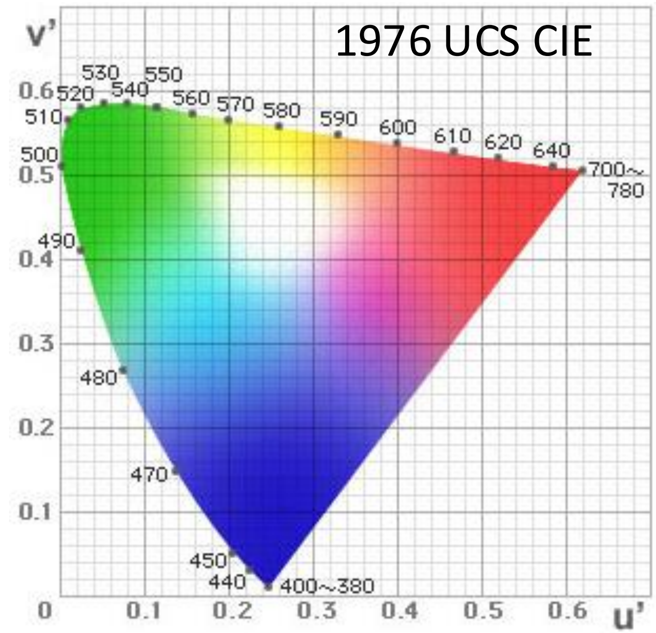
How things actually are at night

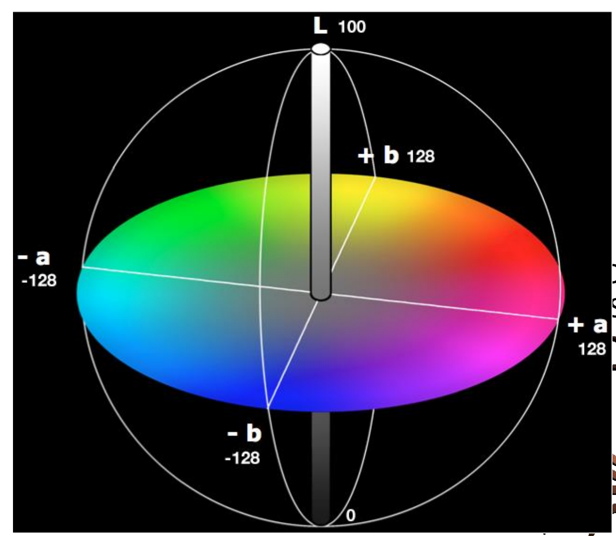
Photopic, or daytime vision senses color from cone cells – but not capable at sensing low light levels

North wall, Yosemite Valley, CA in March

Color spaces







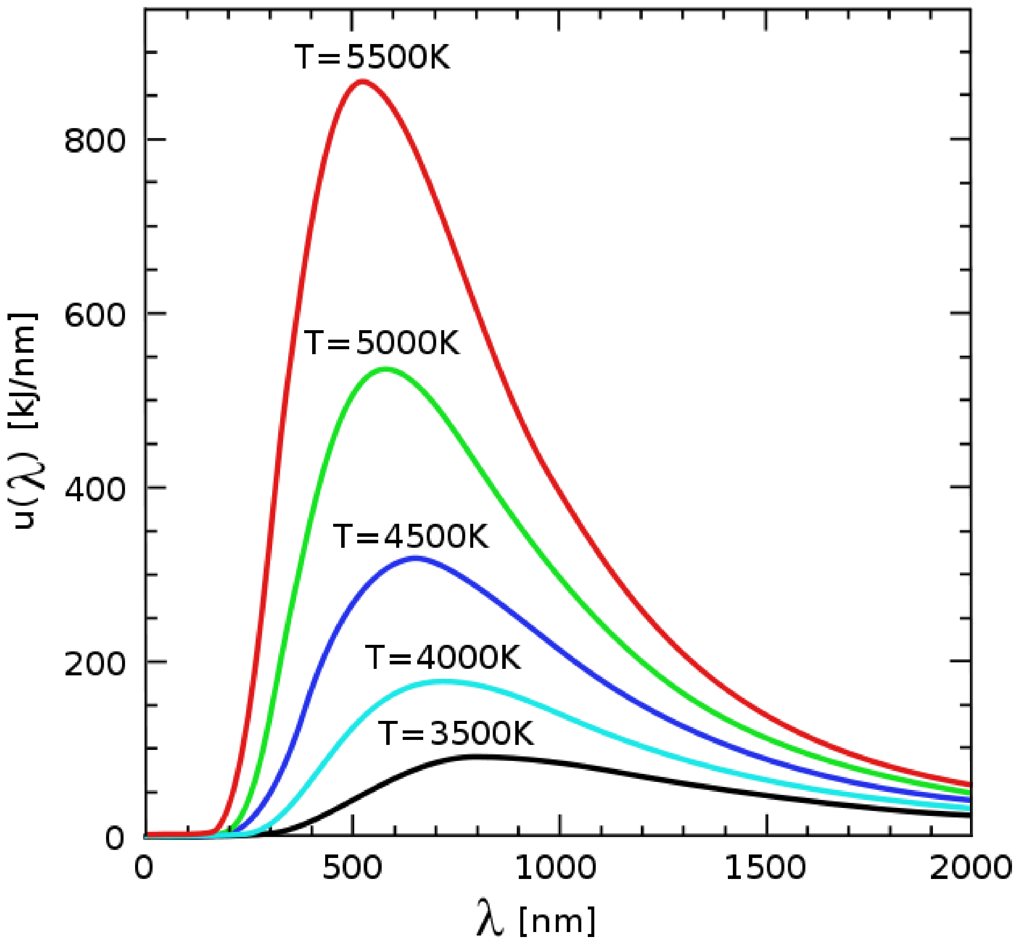
Transforming between 1931 and 1976 spaces

$$u = \frac{4x}{-2x + 12y + 3}; \quad v = \frac{6\,y}{-2x + 12y + 3}$$

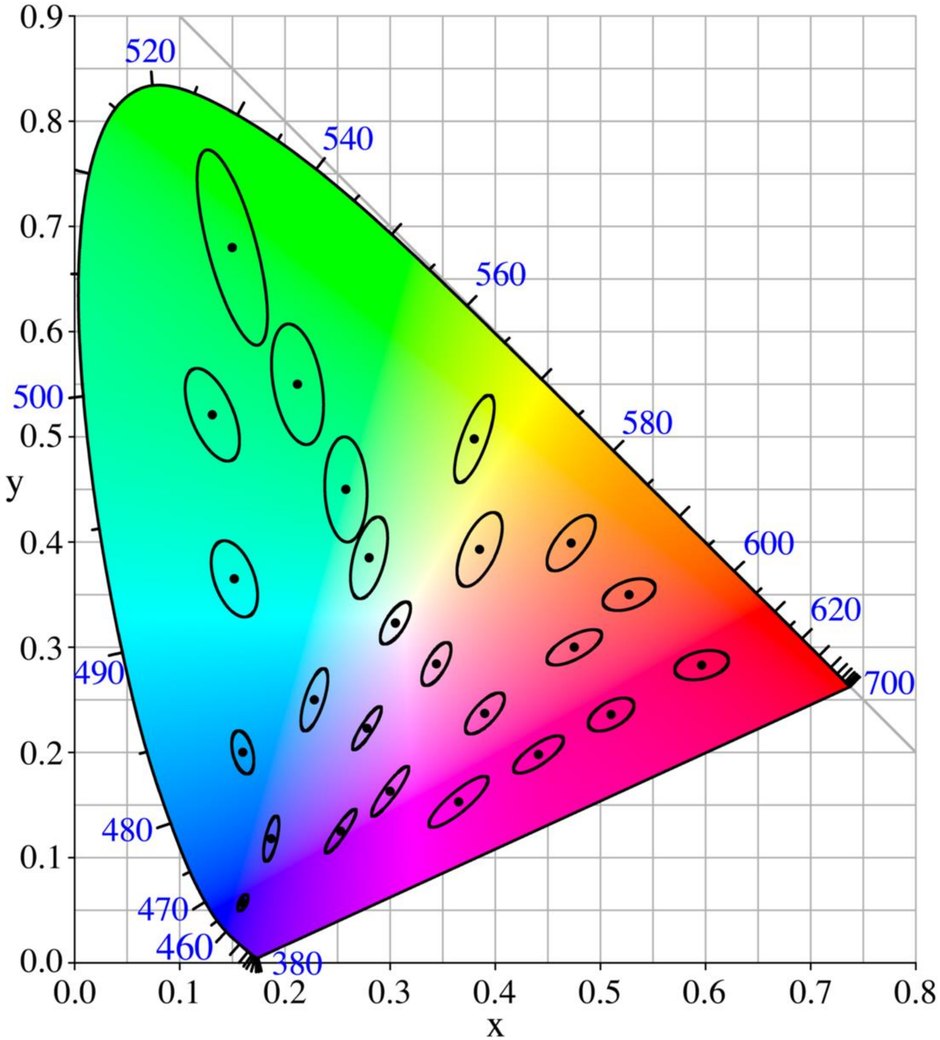
$$u' = u; \qquad v' = \frac{3}{2}v.$$

Planck's law of black body radiation

$$B(\lambda, T) = \frac{2hc^2}{\lambda^5}\left[\frac{1}{exp\left(E_{ph}/k_B T\right) - 1}\right]$$



Limits to color perception

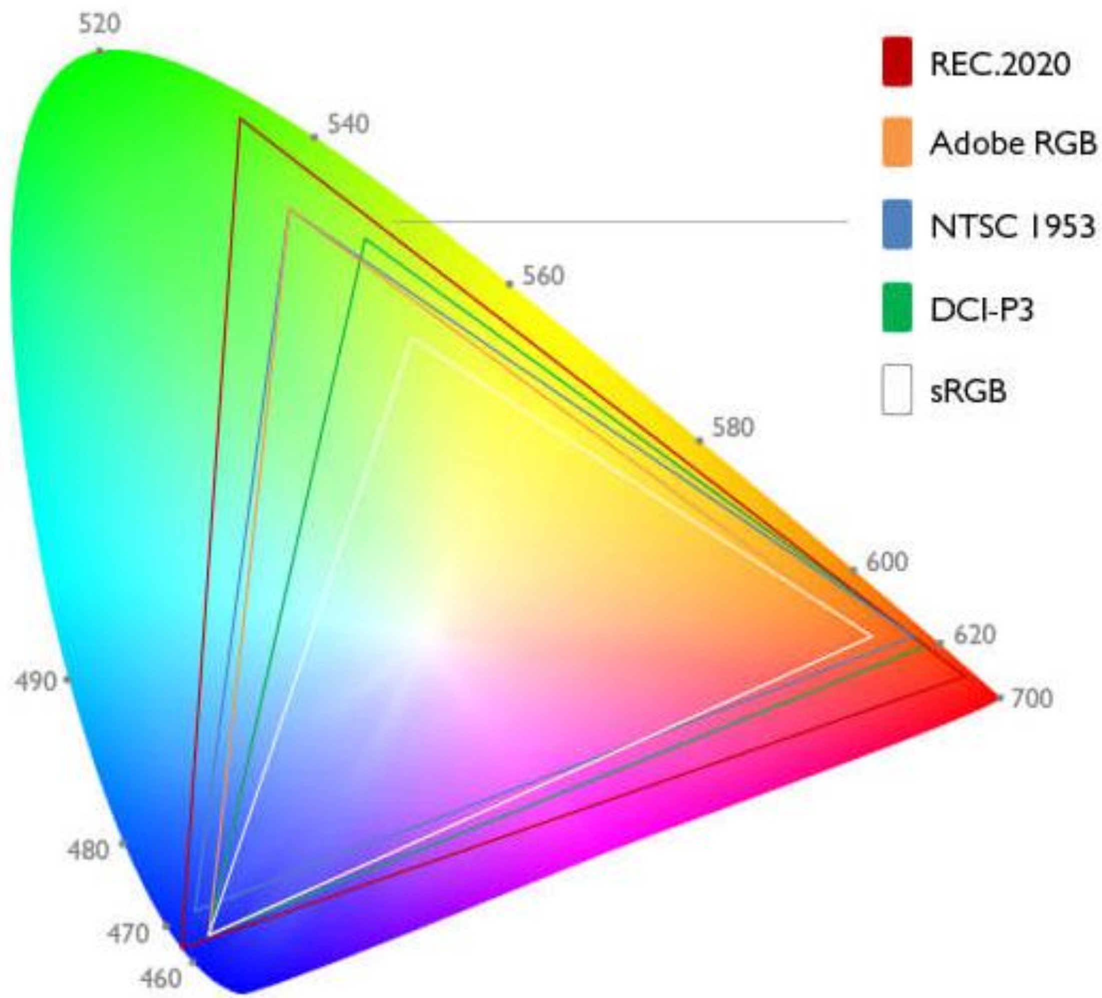


MacAdams Ellipses:

Define the amount of change in color that can be perceived

Each ellipse magnified 10X

Various Display Color Gamuts



Light source definitions

$$\text{External quantum efficiency} = \frac{\text{No. photons viewed}}{\text{No. of electrons injected}} = \frac{q\lambda P_{meas}}{(hc)\, I_{OLED}}$$

$$\text{Internal quantum efficiency} = \frac{\text{No. photons emitted}}{\text{No. of electrons injected}} = \frac{q\lambda P_{meas}}{\eta_{out}\,(hc)\, I_{OLED}}$$

$$\text{Power efficiency} = \frac{\text{Optical power emitted}}{\text{Elect. power injected}} = \frac{P_{meas}}{I_{OLED}V_{OLED}} \quad \text{[W/W]}$$

$$\text{Luminance power efficiency} = \frac{\text{Luminance}}{\text{Elect. power injected}} = \frac{L_{meas}}{I_{OLED}V_{OLED}} \quad \text{[lm/W]}$$

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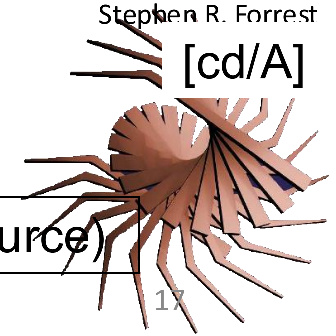
$$\text{Luminance efficiency} = \frac{\text{Luminance}}{\text{Current injected}} = \frac{L_{meas}}{I_{OLED}} \quad \text{[cd/A]}$$



Luminance units: cd/m^2 = nits; cd=lumens/π (for a Lambertian source)

Radiometric and Photometric Quantities

Radiometric units				Photometric units			
Quantity	**Symbol**	**Expression**	**Unit**	**Quantity**	**Symbol**	**Expression**	**Unit**
Radiant flux	Φ_e		W	Luminous flux	Φ		lm
External quantum efficiency	η_{ext}	$\eta_{int}\eta_{out}$	%	Luminous efficiency	η_L	$\frac{L}{j}$	cd/A
Power efficiency	η_P	$\frac{1}{jV}\frac{d\Phi_e}{dS} = \frac{E_e}{jV}$	%, or W/W	Luminous power efficiency	η_{LP}	$\frac{1}{jV}\frac{d\Phi}{dS} = \frac{E}{jV}$	lm/W
Radiant intensity	I_e	$\frac{d\Phi_e}{d\Omega}$	W/sr	Luminous intensity	L_Ω	$\frac{d\Phi}{d\Omega}$	lm/sr
Radiance	L_e	$\frac{d\Phi_e}{dS\,d\Omega\cos\theta}$	W/sr-m^2	Luminance	L	$\frac{d\Phi}{dS\,d\Omega\cos\theta}$	cd/m^2 = lm/sr-m^2
Irradiance	E_e	$\frac{d\Phi_e}{dS}$	W/m^2	Illuminance	E	$\frac{d\Phi}{dS}$	lm/m^2 = lux
Radiant exitance	M_e	$\frac{d\Phi_e}{dS}$	W/m^2	Luminous exitance	M	$\frac{d\Phi}{dS}$	lm/m^2

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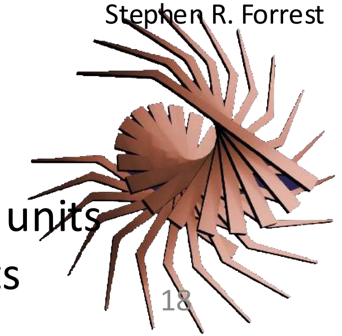


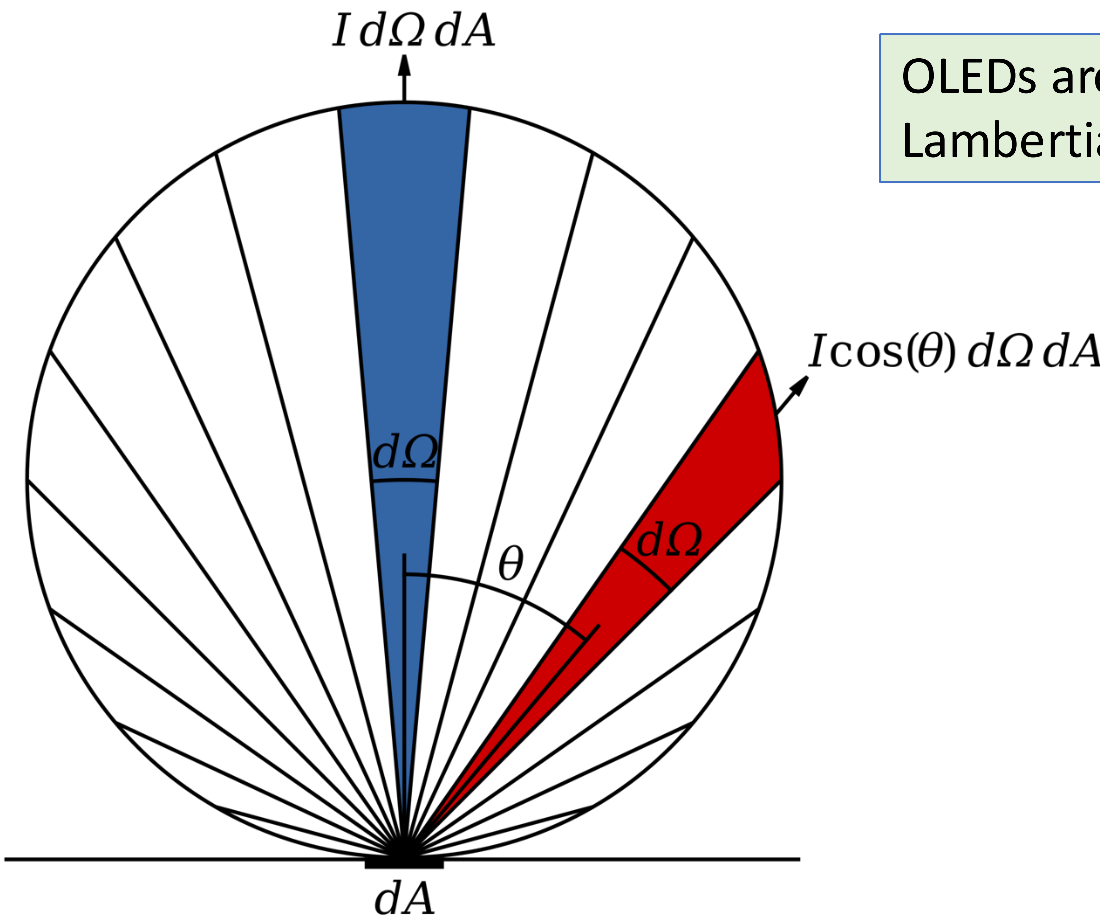
Radiometric: Light source properties quantified using standard scientific units
Photometric: Light source properties quantified by visual *perceptive* units

What is a Lambertian Source?

Lambert's cosine law: The radiant or luminous intensity from a diffuse radiator is proportional to the cosine of the angle , θ, of observation relative to the source.

$$\text{Thus } I = I_0 \cos\theta$$

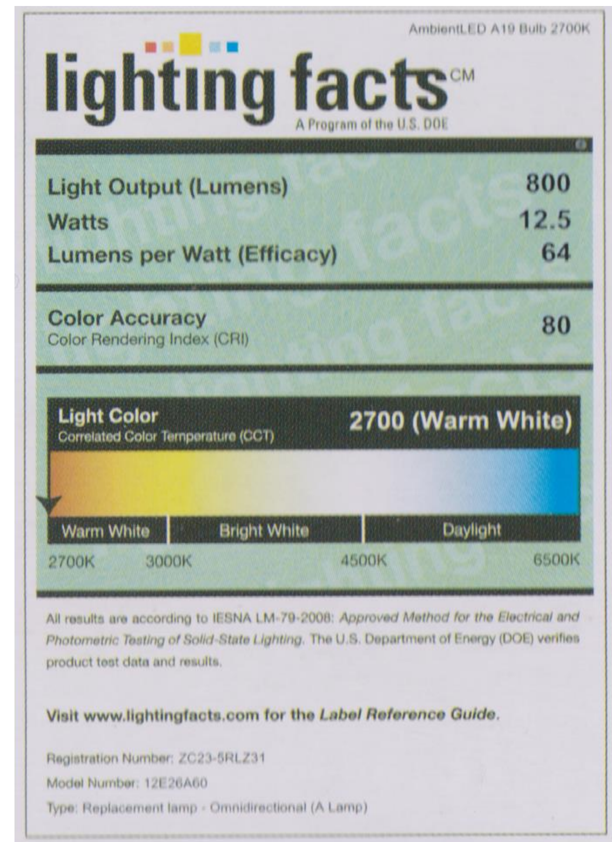
Also called the **cosine emission law**



OLEDs are *approximately* Lambertian sources

Quantifying White Light

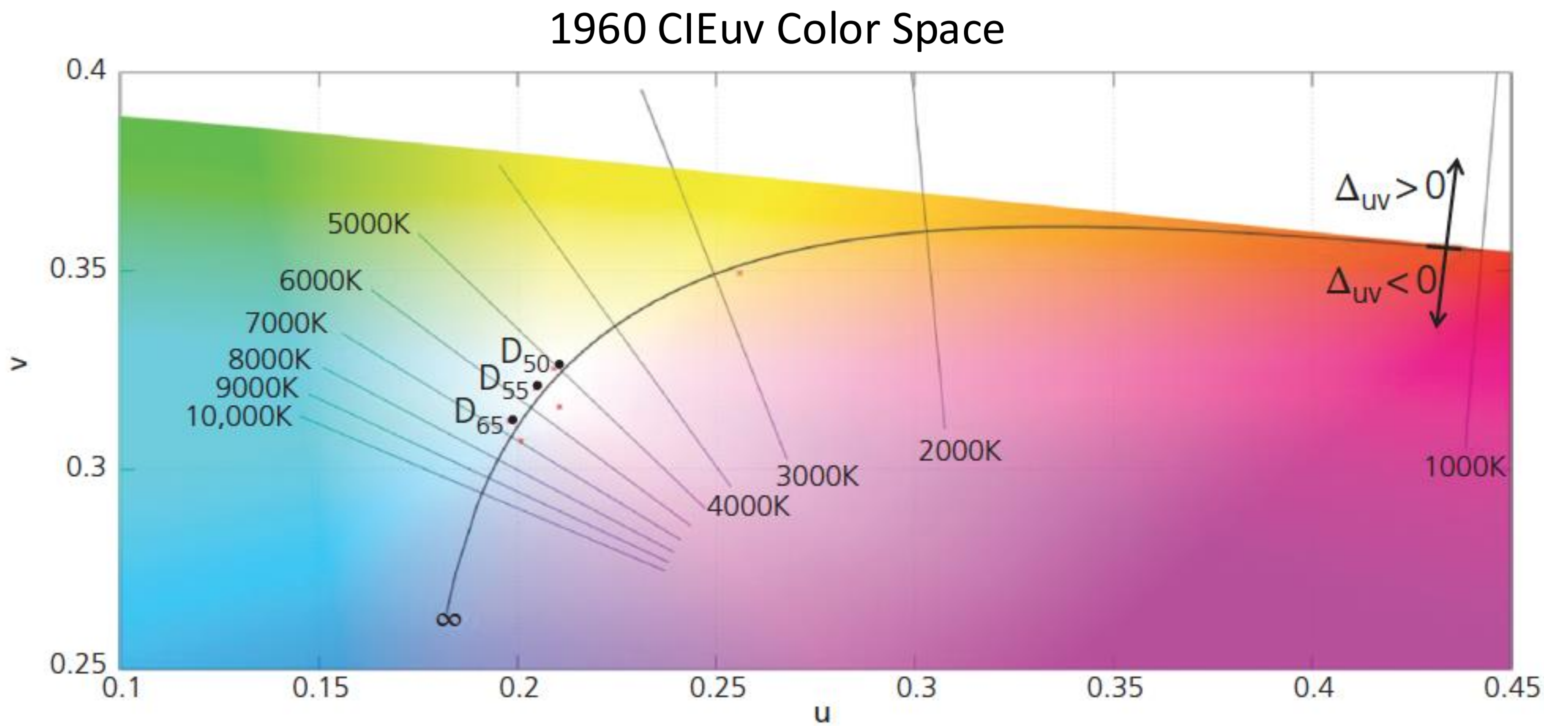
- Color rendering index (CRI)
  - Effect of an illuminant on the appearance of objects compared to that of a reference source (typically a black-body at a *correlated color temperature*, CCT)
  - CRI for white light sources should be >80 (i.e. <20% difference in integrated spectrum compared to black-body)

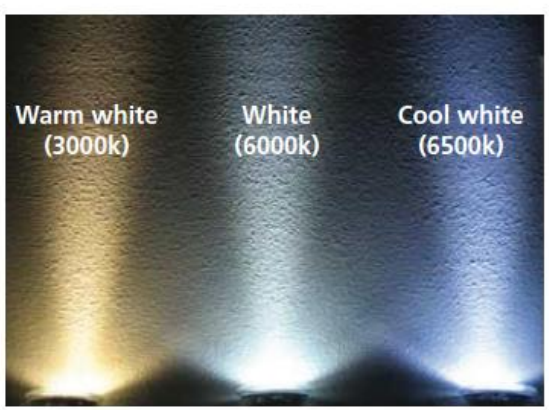


High CRI   Low CRI

Note dull reds

White light color space





Looking at white

Test color samples

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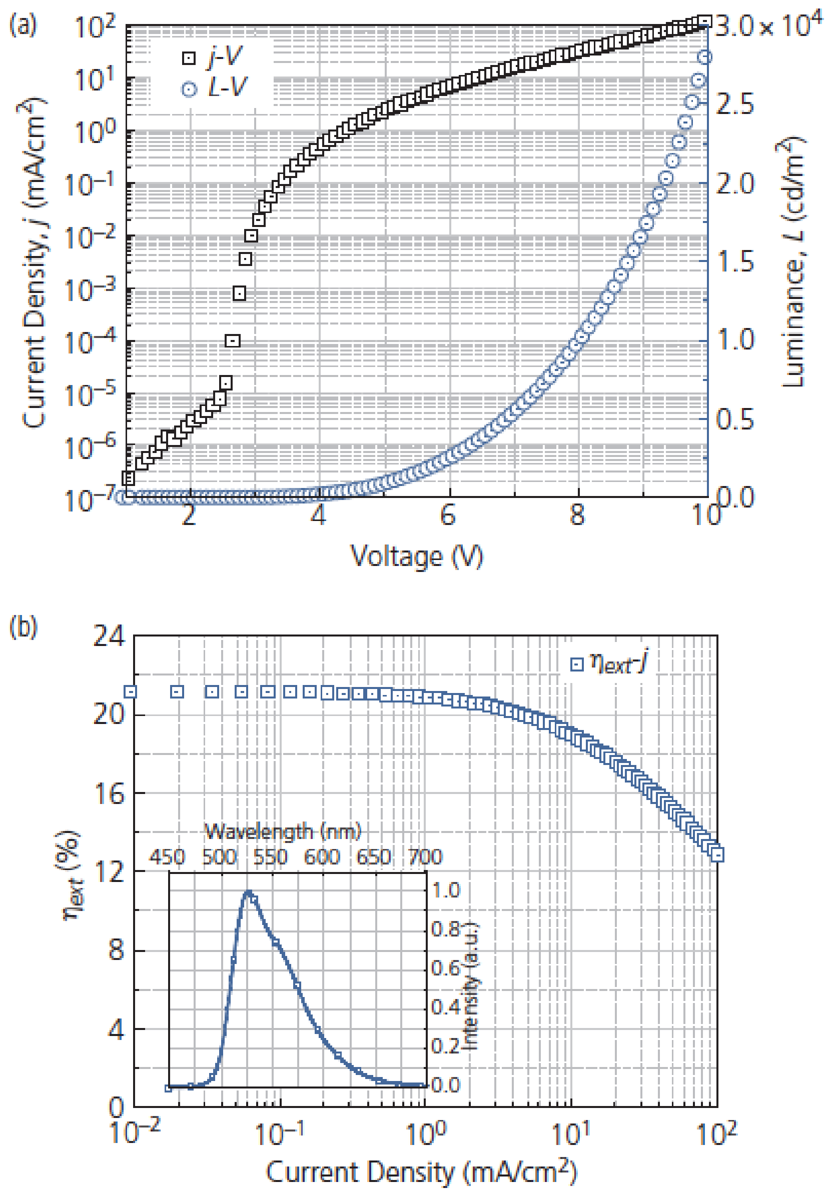
An example data set for an OLED



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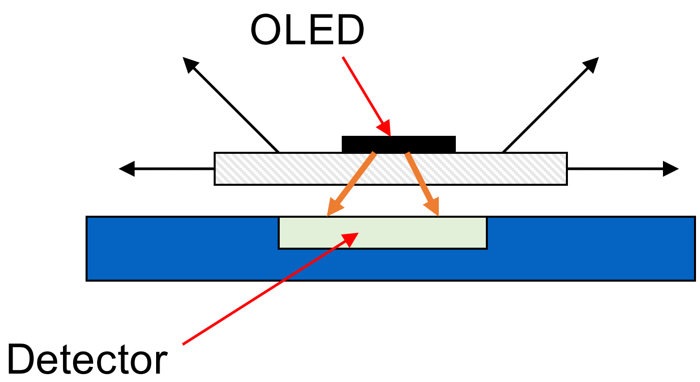
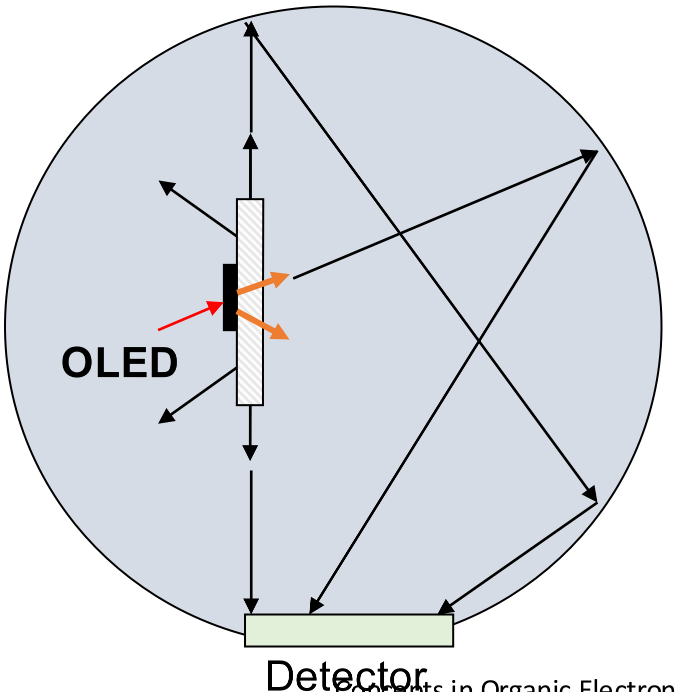
Measuring Quantum Efficiency

<u>External QE</u>



- Measure in forward (viewing) direction only
- Mask waveguided and scattered light
- Place OLED on detector for max. accuracy

<u>Internal QE</u>



- Measure using integrating sphere
- Must correct for losses in structure