LED Lighting Explained Workshop, May 15th 2013

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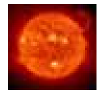
Senior Application Engineer
Philips Lumileds Lighting Company

Presentation Outline

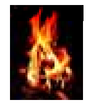
- Light, History & Overview of LED system
- LED Technology
  - Semiconductor physics: pn junction and phosphor
  - LED Manufacturing
  - LED Performance Characteristics
- Color Science
- LED System Design Consideration
  - Thermal
  - Electrical
  - Optical
- Building luminaries
  - A19 Bulb
  - Street Light

Evolution of Lighting

- Nuclear reaction

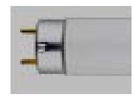


- Chemical reaction (combustion)



- Resistive heating (incandescent)

- Gas discharge (fluorescent, high pressure sodium lamp, metal halide)

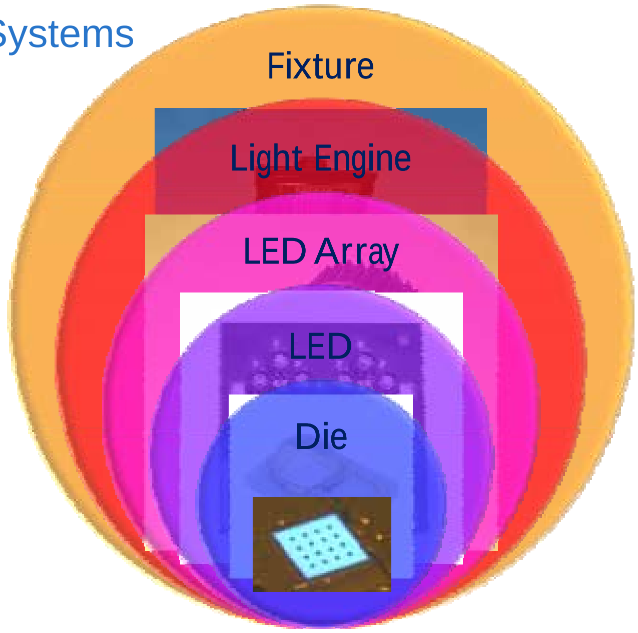


- Electroluminescence (light emitting diodes, LED)

Important Timeline of Light Emitting Diodes (LEDs)

1962	First visible spectrum LED invented by American Nick Holonyak at GE in Syracuse, NY. LED is in red spectrum, based on GaAsP epitaxial layer on GaAs substrate.
1967	George Craford invented first yellow and orange LEDs while in Monsanto using GaAsP epitaxial layer on GaAs substrate. In addition, these LEDs have improved brightness performance with the use on nitrogen doped GaAsP epitaxial layer.
1980s	Commercialization of AlGaAs LEDs
1990	Hewlett-Packard commercializes AlInGaP LEDs
1995	Japan Shuji Nakamura (Nichia) developed high brightness InGaN LEDs (blue) and white LEDs with the use of phosphor.
1998	Lumileds launched the first 1W high power amber, red-orange and red AlInGaP LED (LUXEON I). Introduction of "high power" LEDs to market
2011	Philips wins DOE L Prize for A19 60W retrofit bulb for general use. L Prize 60W bulb must be more than 90 lm/W, operating with less than 10W with minimum of 25,000-hour life at 2700K-3000K, 90 CRI

LED Systems



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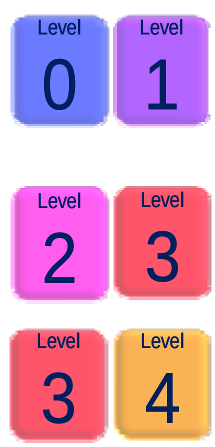

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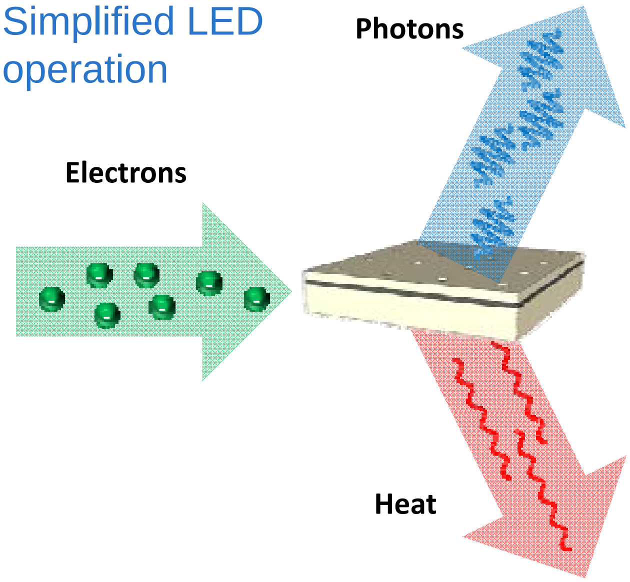
Simplified LED operation

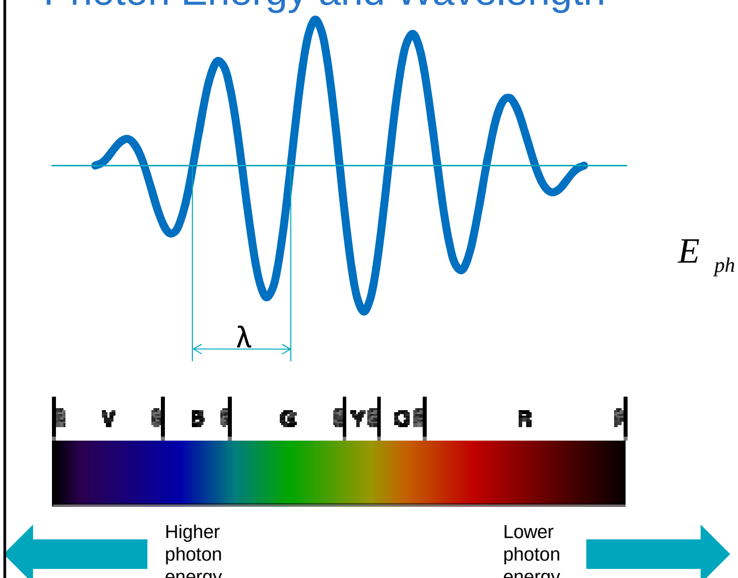
Level 0



$$\eta_Q = \frac{N_{ph}}{N_e}$$

Photon Energy and Wavelength

Level 0



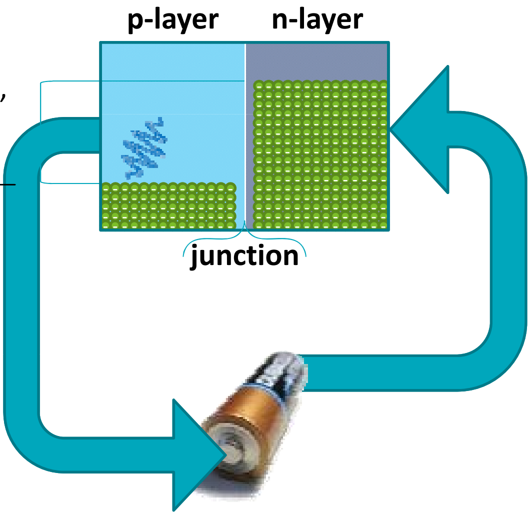
$$E_{ph} = \frac{hc}{\lambda}$$

LED Illustration

Level 0

"Bandgap E_g"

$$E_{ph} = \frac{hc}{\lambda}$$



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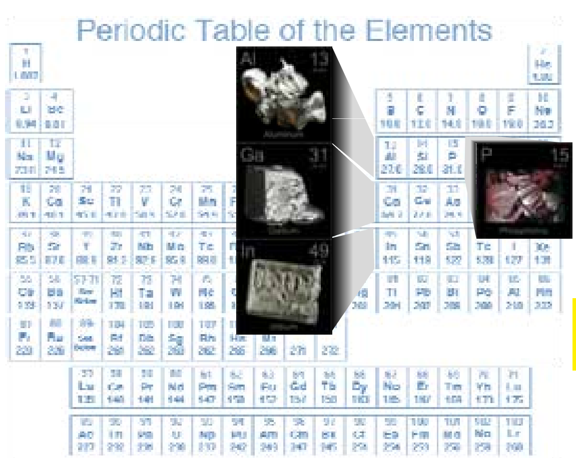
LED Material System - AlInGaP

Level 0



AlInGaP

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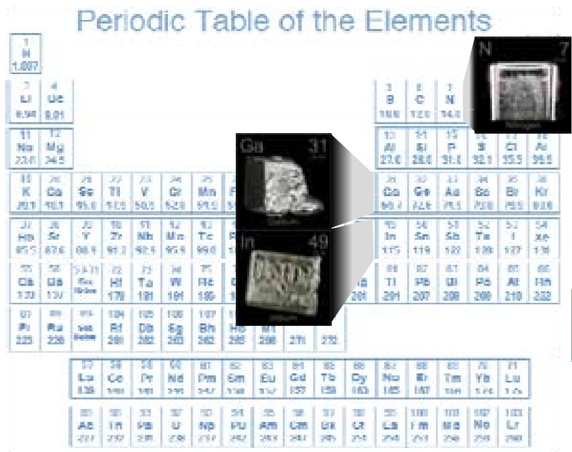
LED Material System - InGaN

Level
0

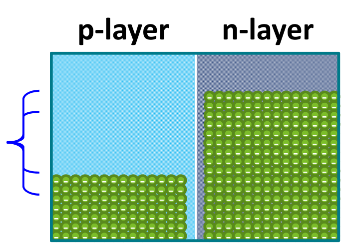


InGaN

How Different Colors Are Produced?

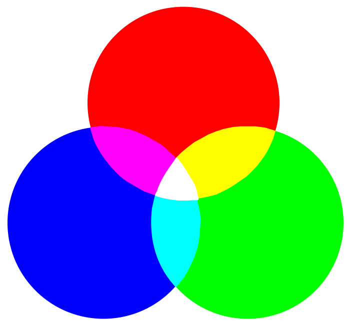
Level
0

Change bandgap, E_g



- Aluminum Indium Gallium Phosphide, $(Al_xGa_{1-x})_{0.5}In_{0.5}P$
- Indium Gallium Nitride, $In_xGa_{1-x}N$

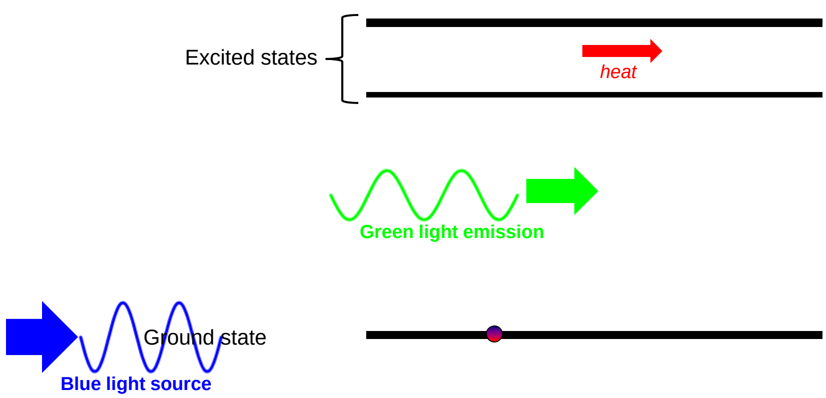
What About White?



- Mix RGB LEDs
- Add phosphor material to blue LED

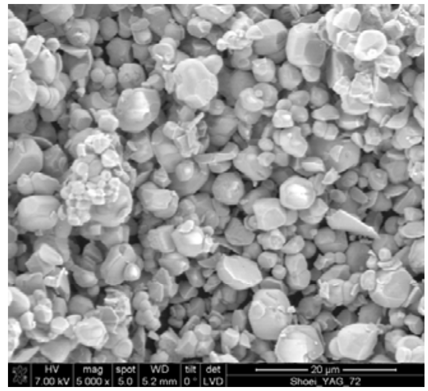
Phosphor – Basic Physics

Electroluminescence vs photoluminescence



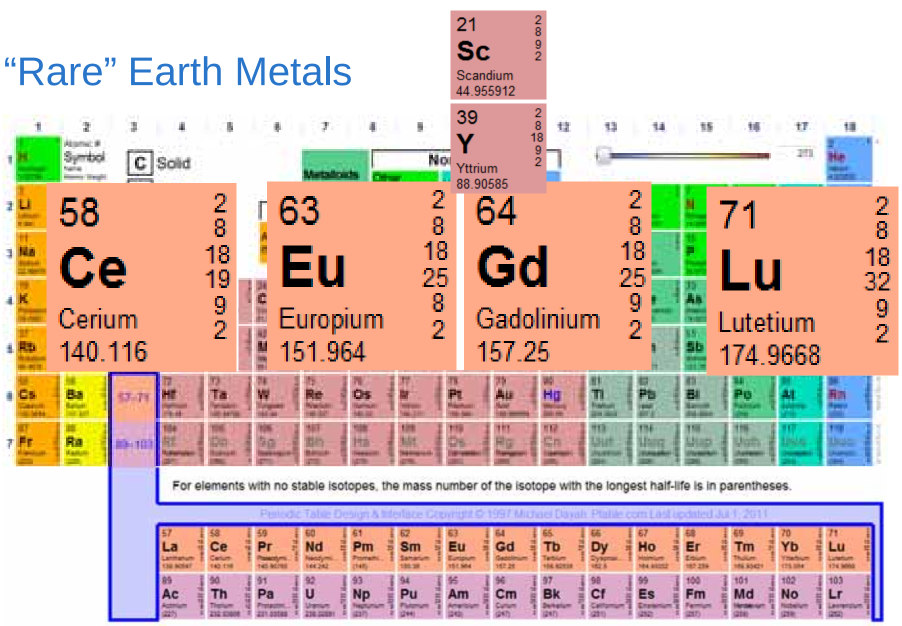
Phosphor Materials

Example of green/yellow phosphor
- YAG:Ce (Yttrium Aluminum Garnet, Cerium doped)
- LuAG:Ce (Lutetium Aluminium Garnet, Cerium doped)



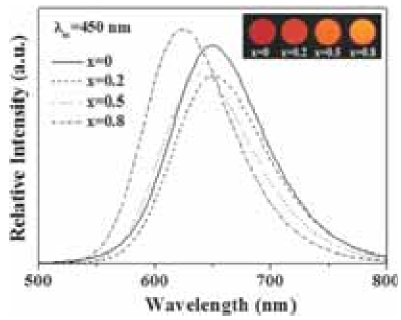
Example of red phosphor
- $(Sr_xCa_{1-x})AlSiN3:Eu$

“Rare” Earth Metals



Example of Phosphor Emission Spectra Control

Spectra of $(Sr_xCa_{1-x})AlSiN_3$:Eu phosphors as a function of Sr content, x



Kim Y et al. ECS J. Solid State Sci. Technol. 2013;2:R3021-R3025

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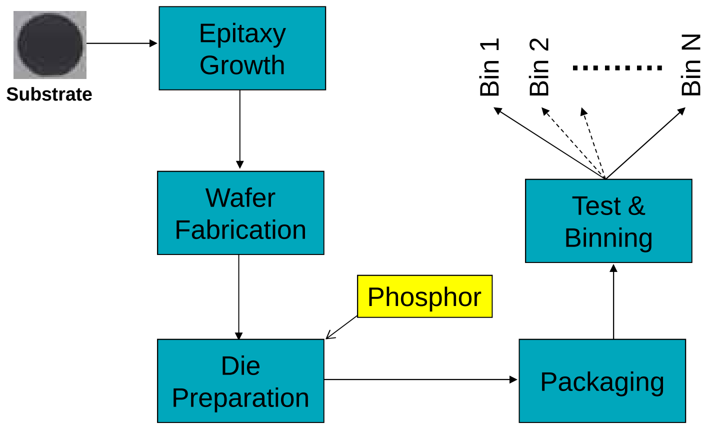
Typical LED Manufacturing Process



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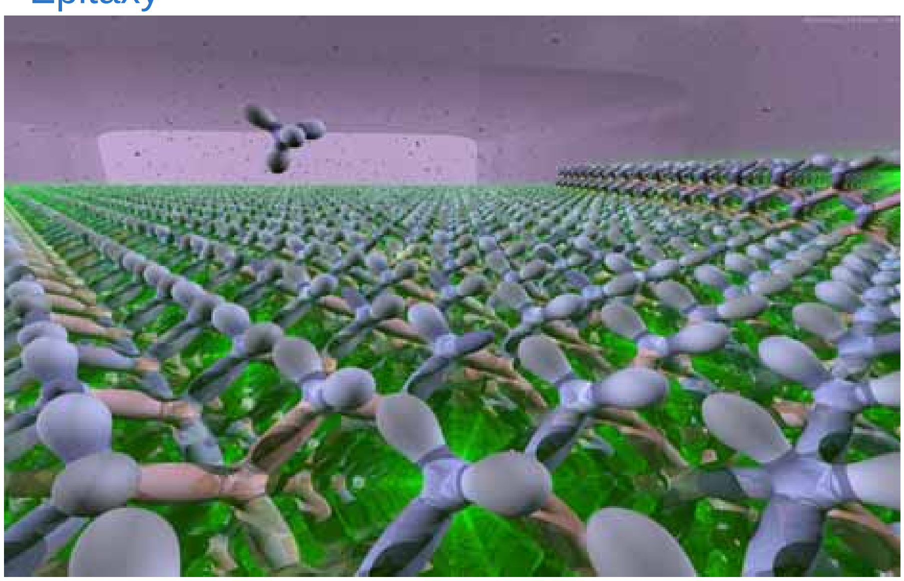
Epitaxy



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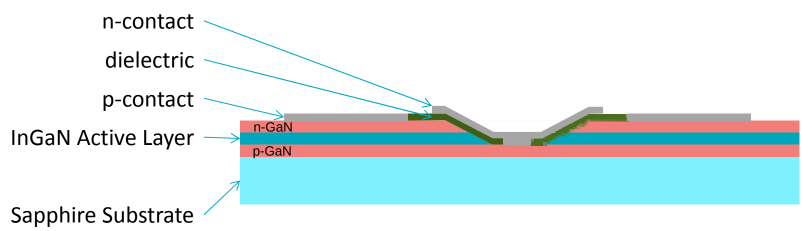
Epitaxy Growth & Wafer Fabrication

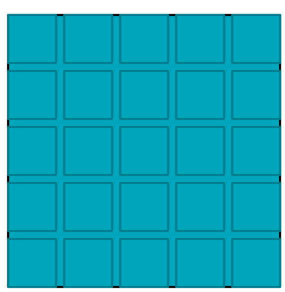


Wafer Fabrication

Die Preparation

Level 0

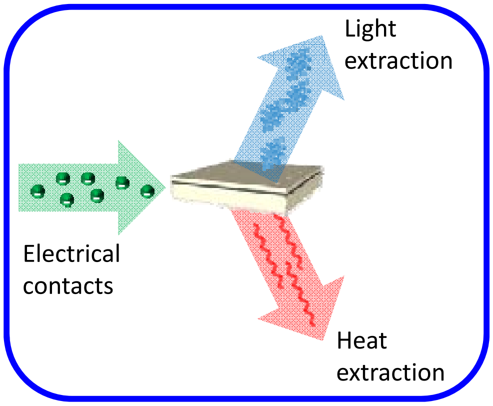
- Testing
- Singulation
- Visual Insp



Die Preparation

Level 1 Packaging

Level 1



Mechanical support and protection

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Level 1 Packaging

Level 1

- Low Power (~0.1W) to Mid Power (~0.5W)

- High Power (> 1W)

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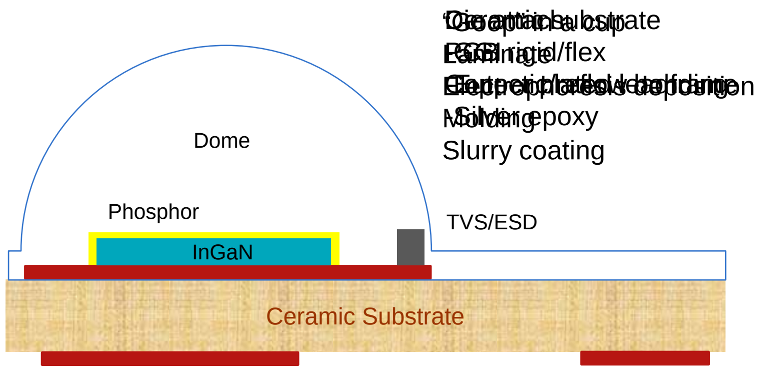
Typical Level 1 LED Package Assembly

Level 1



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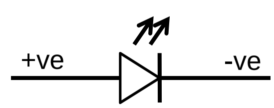
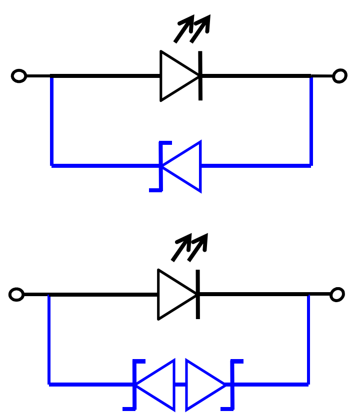
Typical LED Package Electrical Schematics

•AlInGaP is not susceptible to ESD damage



•InGaN chip is



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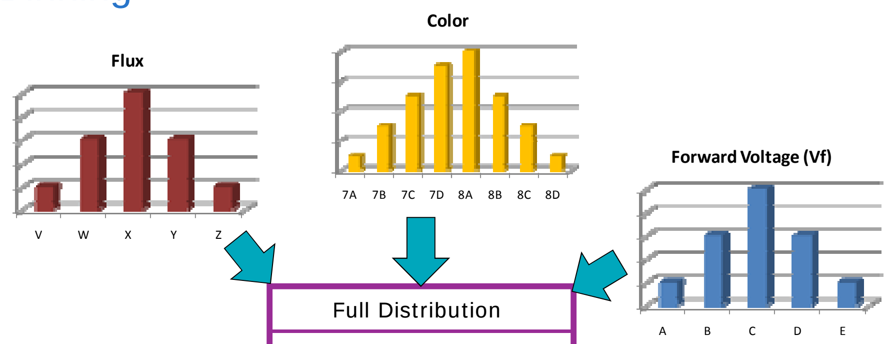
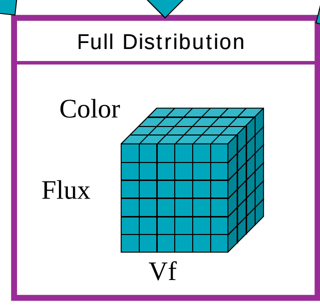
Binning





Bin Code: XYZ or XYYZ
X = flux code
Y = color code
Z = Vf code

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Freedom From Binning

Performance close to real operating condition

Tested "hot", Tj = 85°C instead of 25°C

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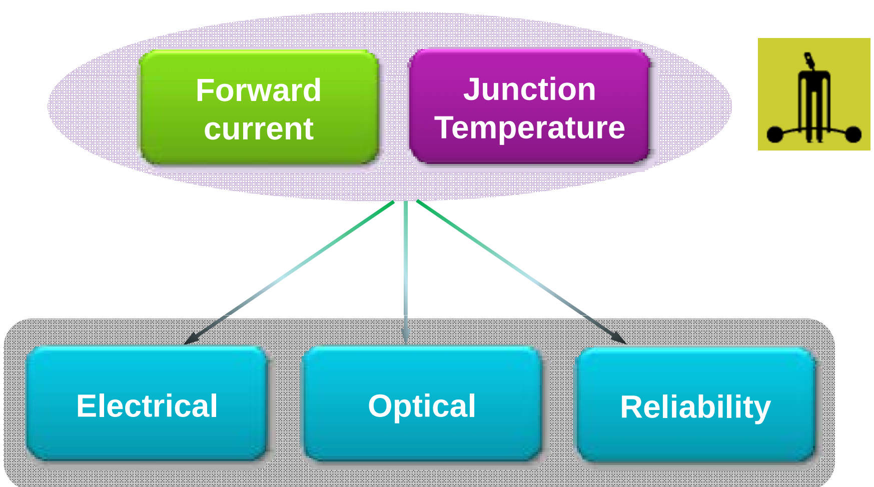
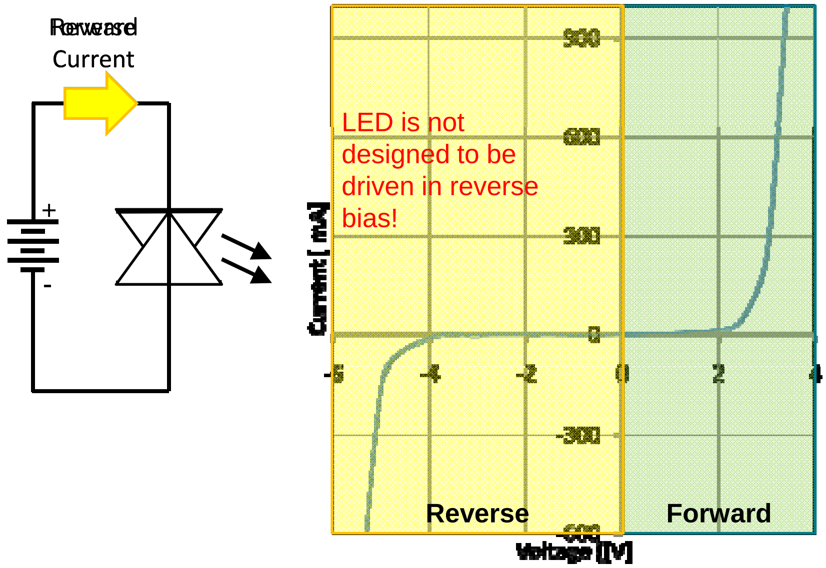
LED Performance Characteristics

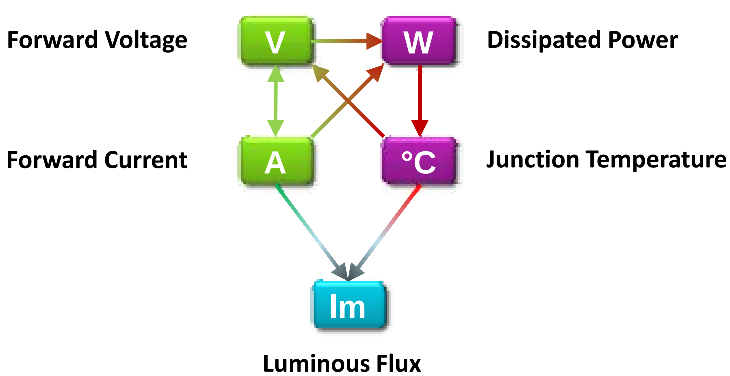


Current – Voltage in Both Forward & Reverse



Parametric Interrelationship

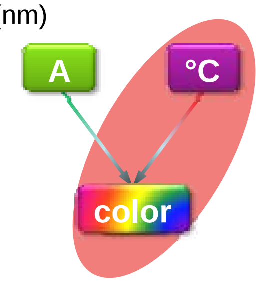
$P = V_f * I_f$



What About Color?

Color parameters:

- Peak wavelength (nm)
- Color points (*cx, cy*) in CIE 1931 color space or in (*u', v'*) CIE 1976 color space
- Dominant wavelength (nm)



$$\frac{\Delta\lambda_{peak(dom)}}{\Delta T} = +0.5\,\text{nmV/°C}$$

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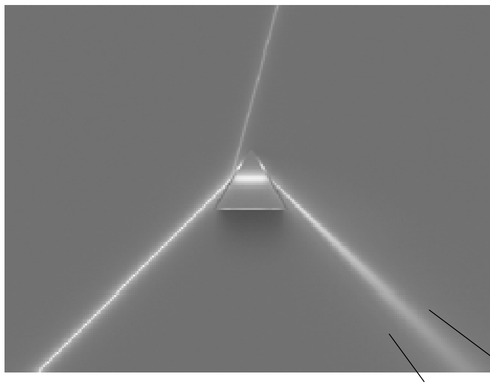
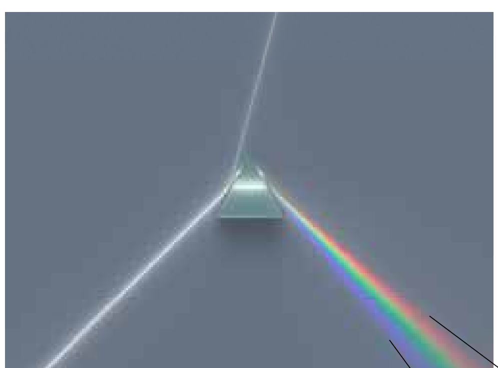
There is no color in physics class

No Laws or Theorems



400nm 800nm

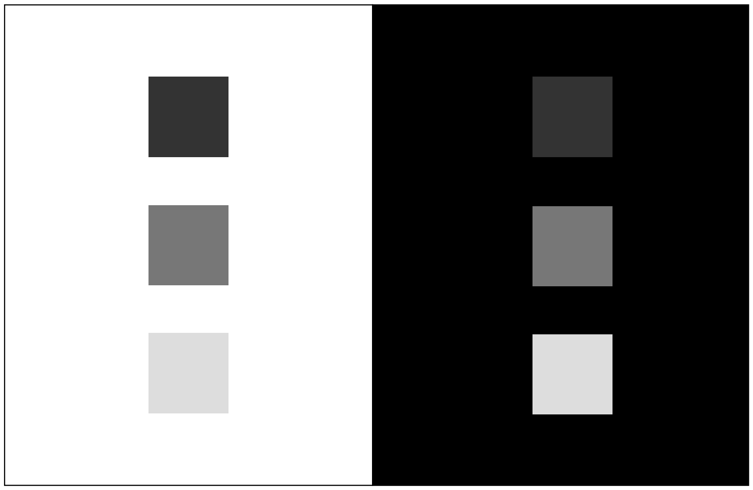
It's all in your head… Human perception



Human eyes response to brightness and color are experimentally based

400nm 800nm

Fun Stuff – Eye Tricks



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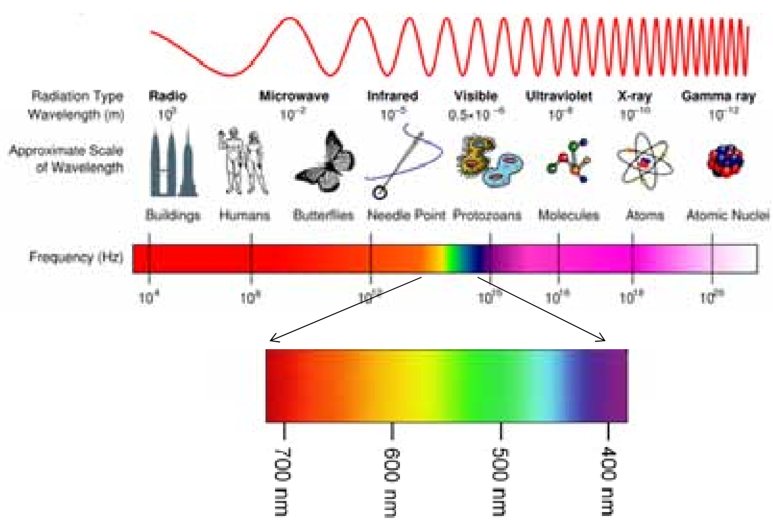
Visible Radio



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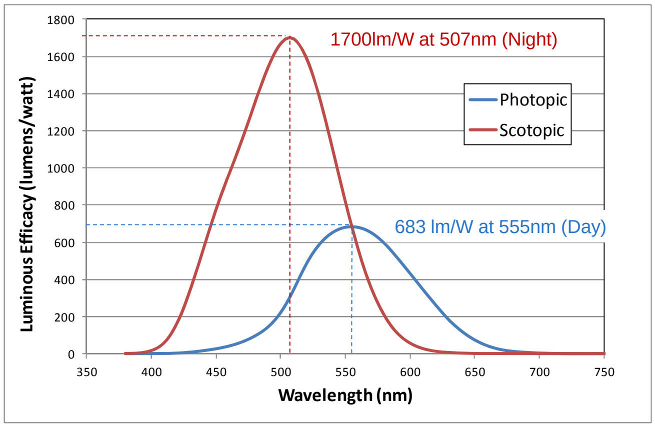
Photopic Scotopic Mesopic



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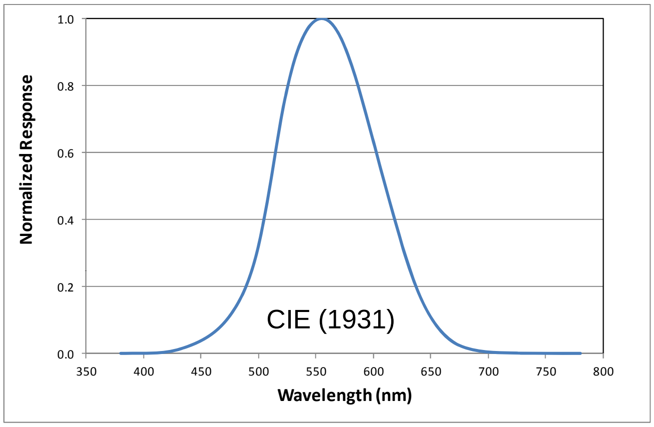
Photopic Eye Response (Luminosity Function, V(l)) as Defined by CIE 1931



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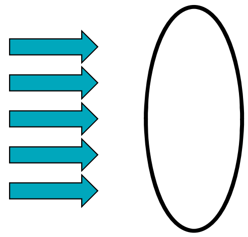
Light Measurement - FLUX



	Photometric	Radiometric
Flux symbol	Φ_V	Φ_E
Units	Lumen (lm)	Optical watts (W_{opt})
Weighting function	$V(\lambda)$	none

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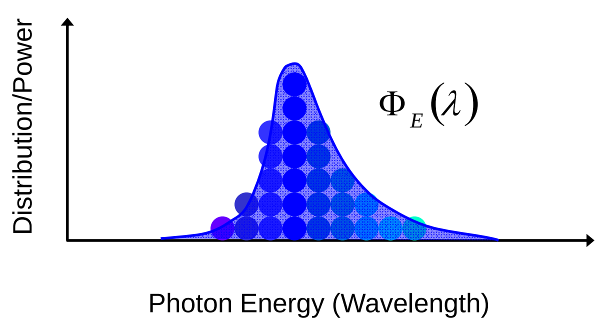
Flux Calculation

- What's needed?
- Spectral Power Distribution (SPD)

$$E_{ph} = \frac{hc}{\lambda}$$



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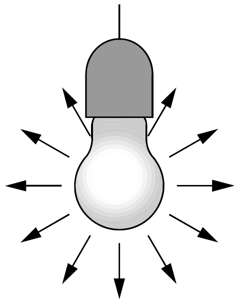
Flux Calculation (continue)



Photometric Flux

$$\Phi_V = \qquad \Phi_E(\lambda)$$

Radioometric Flux

$$\Phi_E = \int_{\lambda=380}^{\lambda=780} \Phi_E(\lambda)d\lambda$$

1 W Radiant Flux at 555 nm = 683 lumens

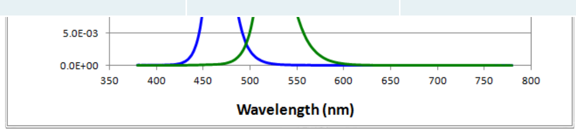
Example: Photometric Flux for Blue and Green LEDs

- Blue and Green LEDs with one watt of optical power

$$\Phi_V = 683 \int_{\lambda=380}^{\lambda=780} V(\lambda)\Phi_E(\lambda)d\lambda$$

$\Phi_E(\lambda)$

	Total Power (W_{opt})	Total Luminous Flux (lm)
Blue LED	1.0	71
Green LED	1.0	515



Color Measurements

- RECALL…
  - Peak wavelength (nm)
  - Color points (*x, y*) in CIE 1931 color space or in (*u', v'*) CIE 1976 color space
  - Dominant wavelength (nm)

  Let's define these parameters

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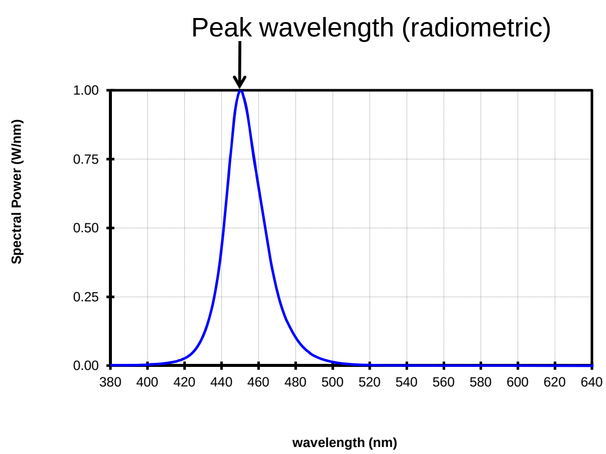
Peak Wavelength



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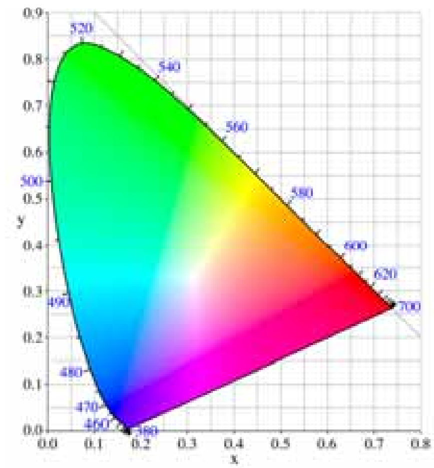
Color Points

- Create color space



CIE 1931

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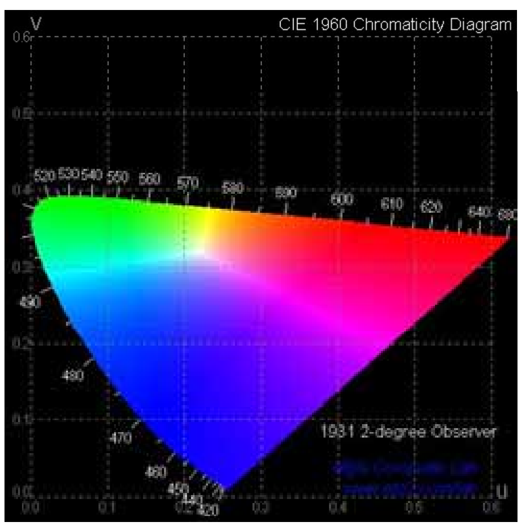
Another Color Space



CIE 1960

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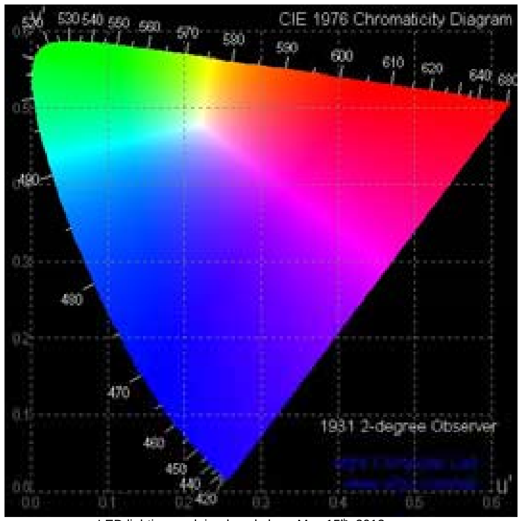
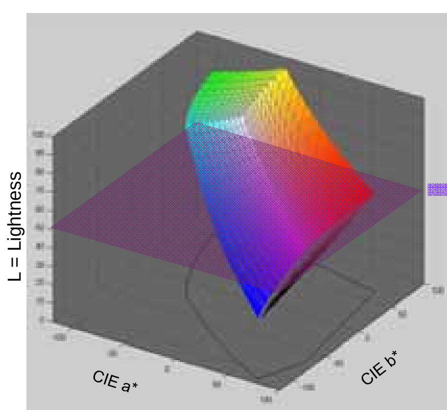
Or Another One?



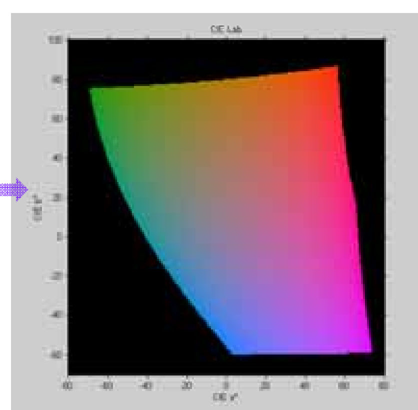
CIE 1976

Last One? … and many more…..

CIE 1976 L*a*b*

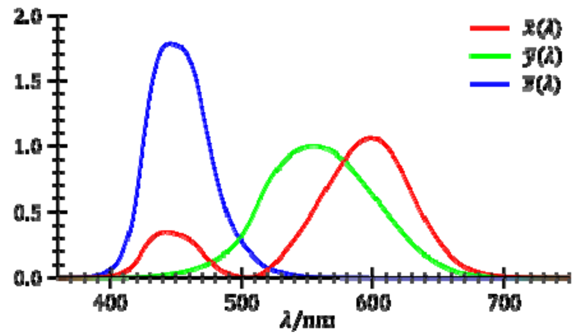


Slice at L=50



CIE 1931 Color Matching Functions

- Define human eye response to each red, green and blue stimuli



CIE 1931 Color Definition

- Tristimulus X, Y, Z → R, G, B
- Define red flux, green flux and blue flux.

$$X = \int \Phi_e(\lambda)\ \bar{x}(\lambda)\ d\lambda$$
$$Y = \int \Phi_e(\lambda)\ \bar{y}(\lambda)\ d\lambda$$
$$Z = \int \Phi_e(\lambda)\ \bar{z}(\lambda)\ d\lambda$$

Unit for X, Y and Z is lumen

CIE 1931 Color Points (*x, y*)

- Define red, green and blue flux ratio

  x = X / (X + Y + Z)
  y = Y / (X + Y + Z)
  z = Z / (X + Y + Z)

- Normalization

  x + y + z =1 ➡ **(*x, y*) chromaticity color points in CIE 1931 color space**

- For more details, see "*Wyszecki & Stiles (Wiley Series), Color Science: Concepts and Methods, Quantitative Data and Formulae*"

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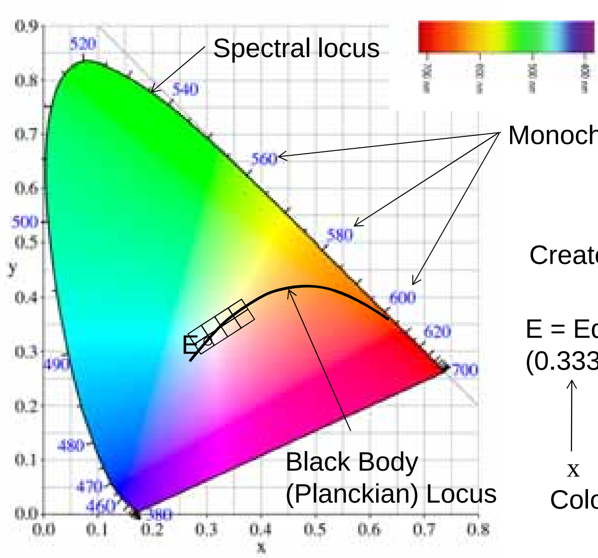
The CIE 1931 xyY Color Space



Create color bins

E = Equal energy point
(0.3333, 0.3333)

x y
Color points

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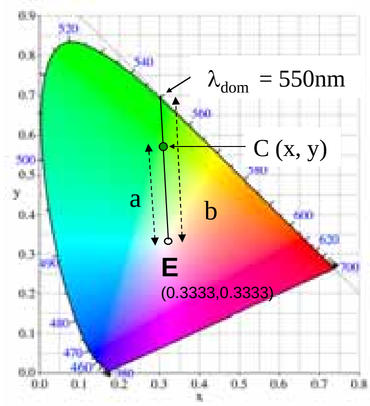
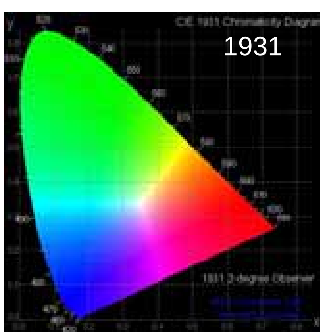
Now We Can Finish of Dominant Wavelength Color Definition

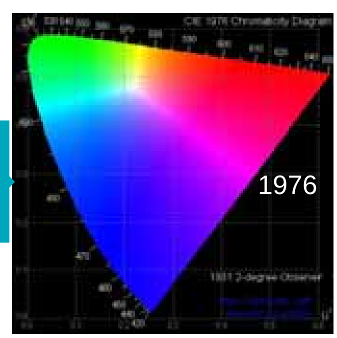
- Light of similar "hue"
- Color purity = a/b



CIE 1931 / CIE 1976 Color Space Conversion



$$x = 9u' / (6u' - 16v' + 12)$$
$$y = 4v' / (6u' - 16v' + 12)$$



Recap….

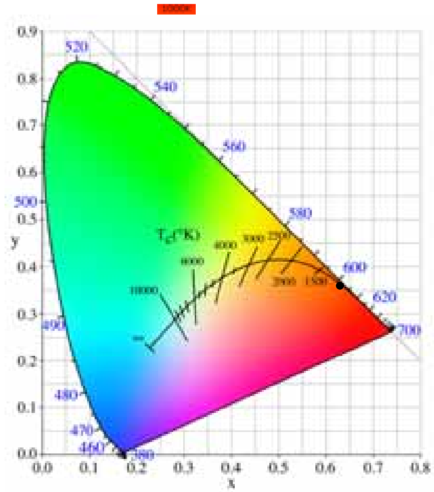
- Peak wavelength (nm)
- Color points (*x*, *y*) in CIE 1931 color space
- Dominant wavelength (nm)

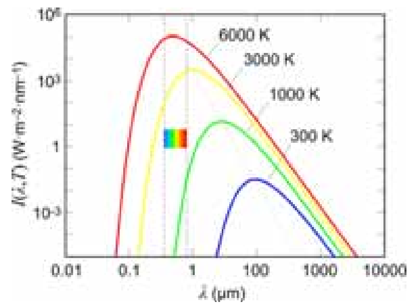
Other LED parameters to describe “white” color?

White Color

- Correlated Color Temperature (CCT, in K)
- Color Rendering Index (CRI, dimensionless, between 0 to 100)

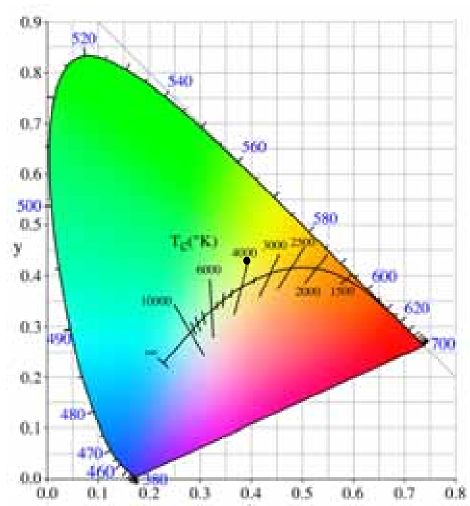
Color Temperature





CORRELATED Color Temperature (CCT)

- Commonly used color bins for solid state lighting are defined in "*ANSI ANSLG C78.377: Specifications for the Chromaticity of Solid State Lighting Products*"
- 2700K, 3000K,3500K, 4000K, 4500K, 5000K, 5700K & 6500K



Color Rendering

Presentation Outline

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  - Semiconductor physics: pn junction and phosphor
  - LED Manufacturing
  - LED Performance Characteristics
- Color Science
- **LED System Design Consideration**
  - **Thermal**
  - Electrical
  - Optical
- Building luminaries
  - A19 Bulb
  - Street Light

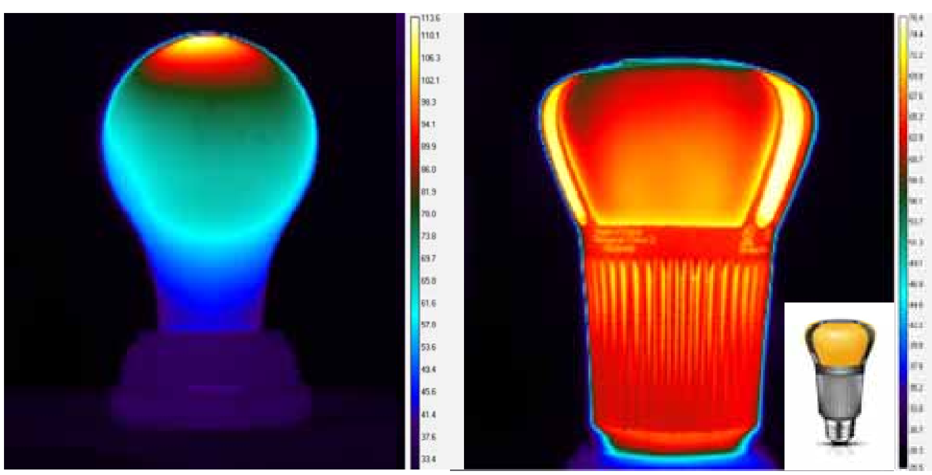
What to Consider When Building a LED System?

Level 2

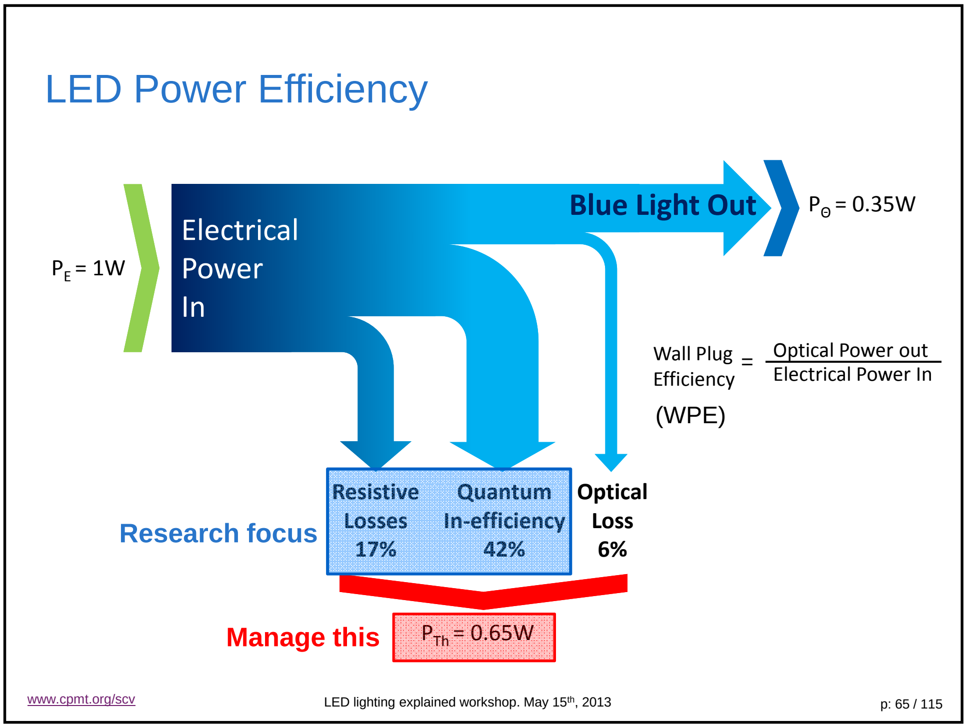
Level 3

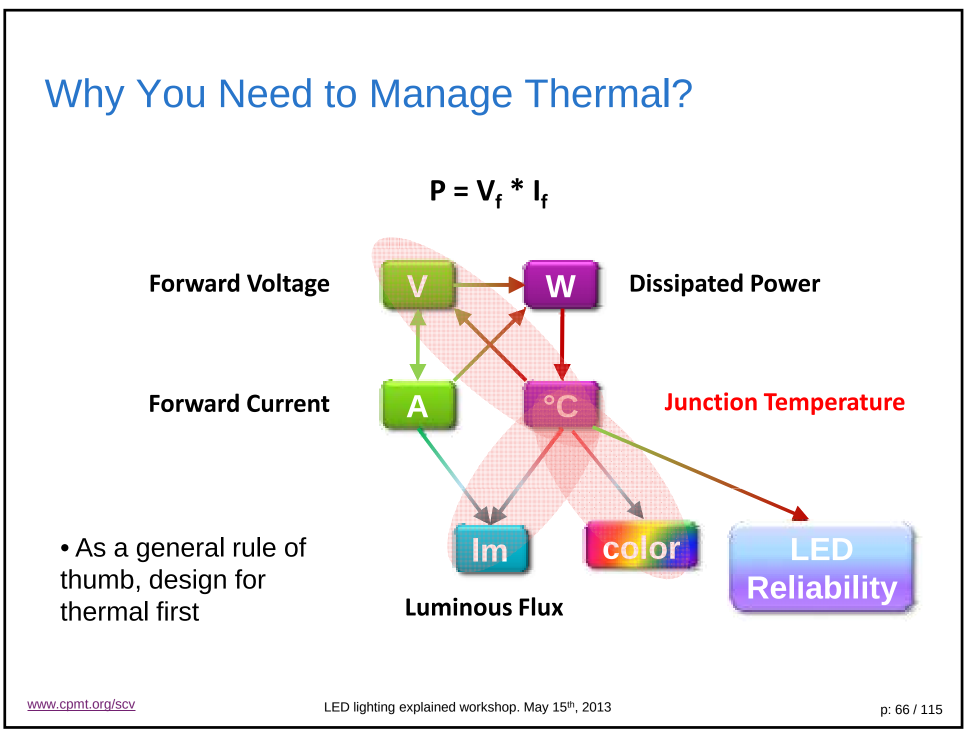
1) Thermal
2) Electrical
3) Optics

Thermal – Tungsten versus LED Bulb



40 Watt Incandescent   Philips 60W L Prize


LED Power Efficiency
Electrical
Power
In
P_E = 1W
Blue Light Out
P_Θ = 0.35W
Wall Plug Efficiency = Optical Power out / Electrical Power In
(WPE)
Resistive Losses 17%
Quantum In-efficiency 42%
Optical Loss 6%
Research focus
Manage this
P_{Th} = 0.65W
www.cpmt.org/scv
LED lighting explained workshop. May 15th, 2013
p: 65 / 115


Why You Need to Manage Thermal?
$P = V_f * I_f$
Forward Voltage
V
W
Dissipated Power
Forward Current
A
°C
Junction Temperature
• As a general rule of thumb, design for thermal first
lm
color
LED Reliability
Luminous Flux
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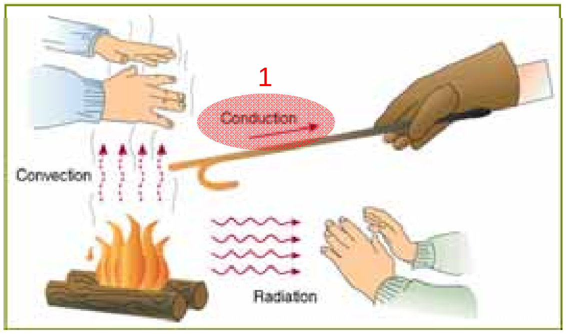
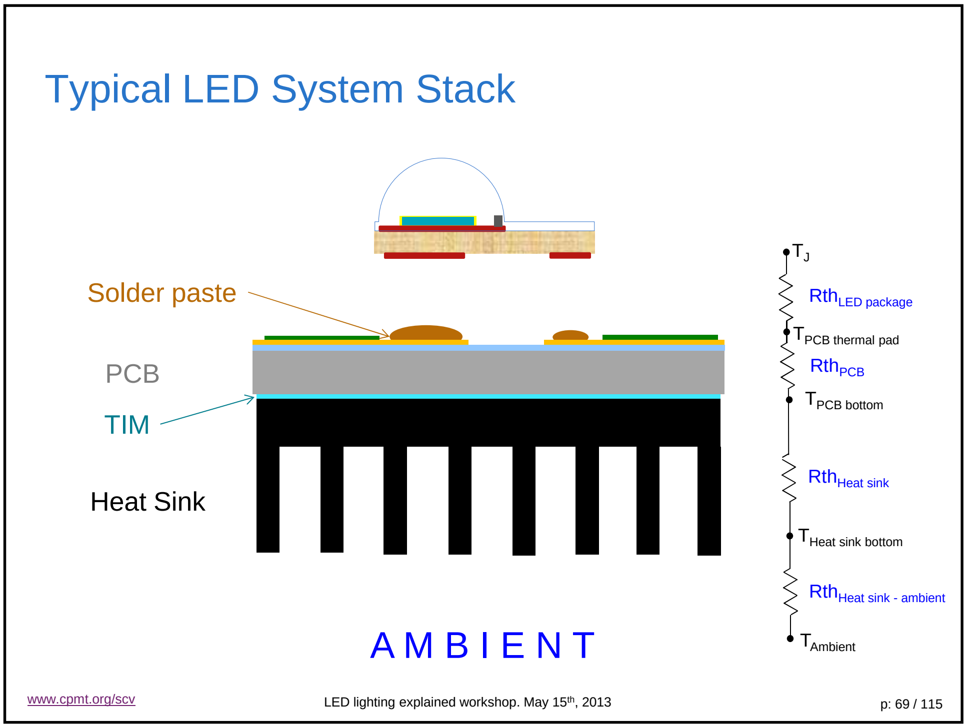
Keep LED Junction Temperature Low. How?



Thermal Resistance (Rth)

- Rth = $(T_1 - T_2) / P_{heat\ dissipation}$
- Unit in K/W or °C/W

Thermal Parameters	Electrical Parameters
Resistance (K/W)	Resistance (ohms)
Temperature difference (K)	Potential difference (V)
Heat flow (W)	Current flow (A)


Typical LED System Stack
Solder paste
PCB
TIM
Heat Sink
AMBIENT
T_J
Rth_LED package
T_PCB thermal pad
Rth_PCB
T_PCB bottom
Rth_Heat sink
T_Heat sink bottom
Rth_Heat sink - ambient
T_Ambient
www.cpmt.org/scv
LED lighting explained workshop. May 15th, 2013
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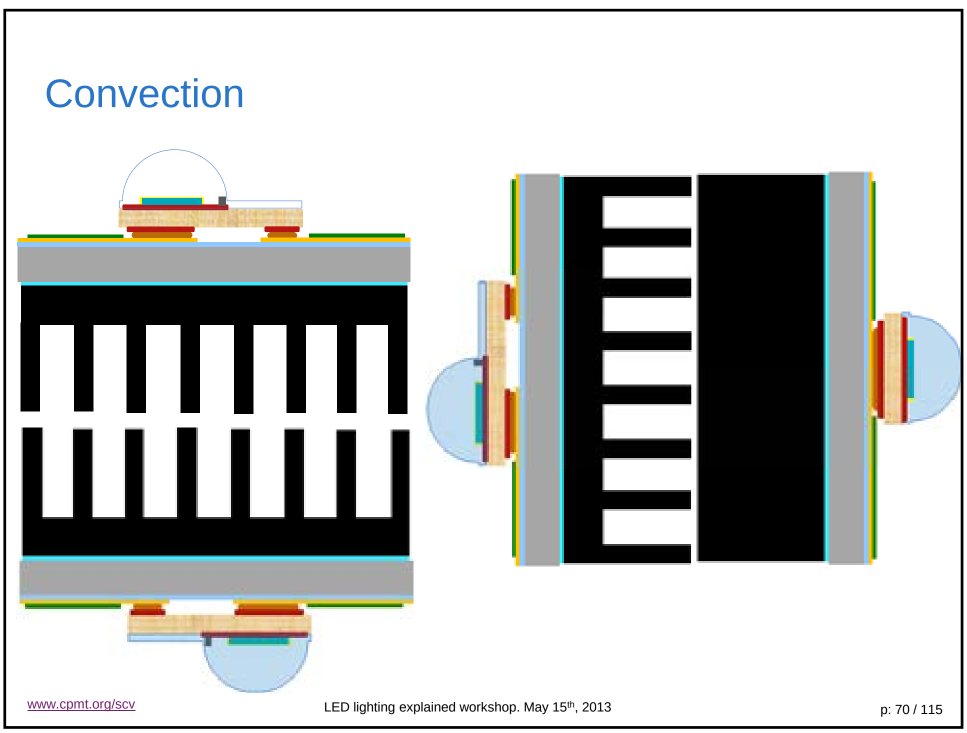
Convection
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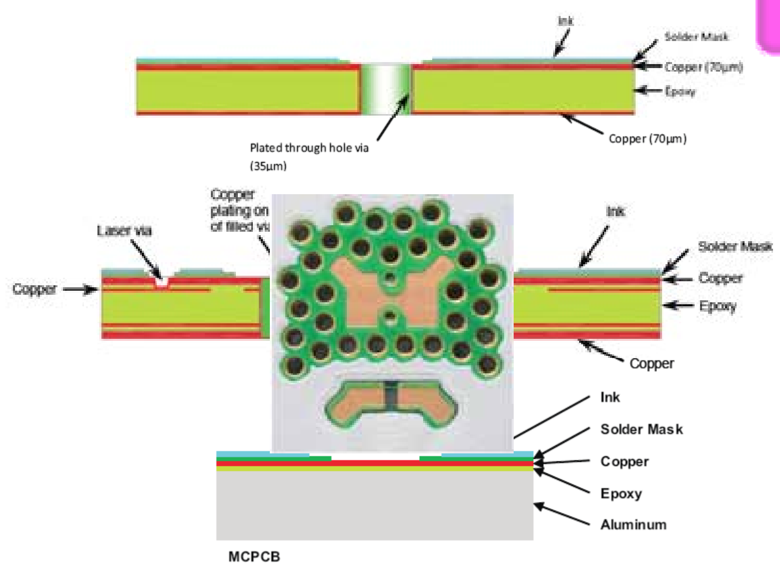
PCB Construction & Design

Level 2



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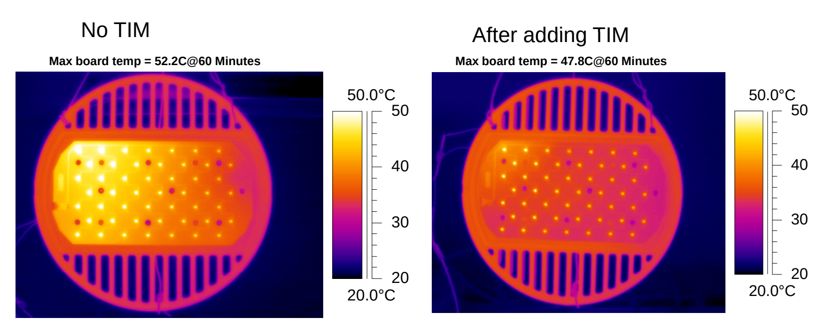
Thermal Interface Material (TIM)



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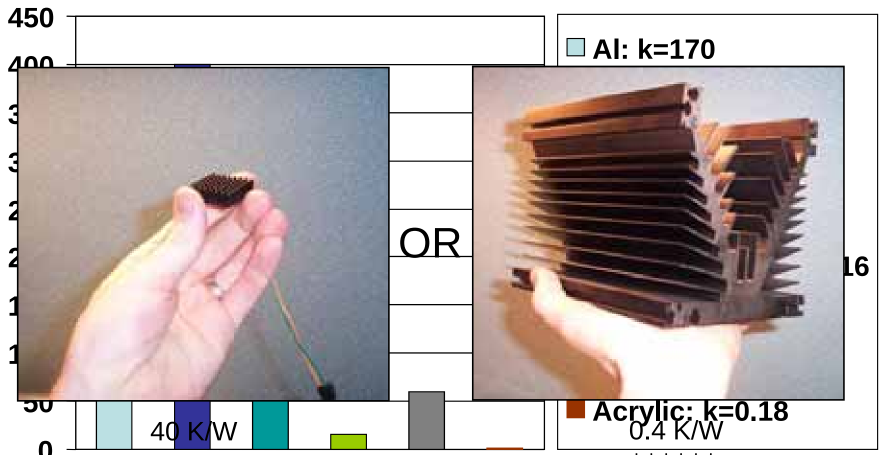
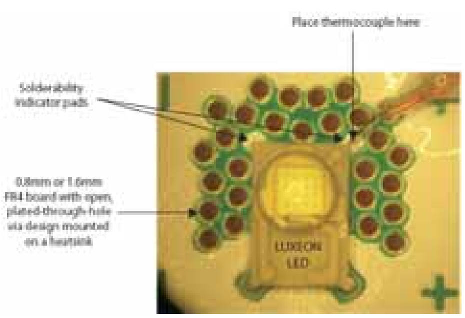
Heat Sink

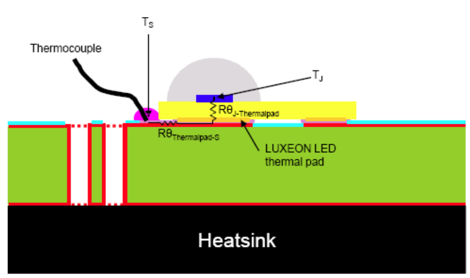


Thermal Conductivity Units are in W/mK.

Junction Temperature Measurement

- Use thermal resistance equipment
- Manufacturer's application notes on Ts method (compare to IC, temperature characterization parameter, y_{JT})





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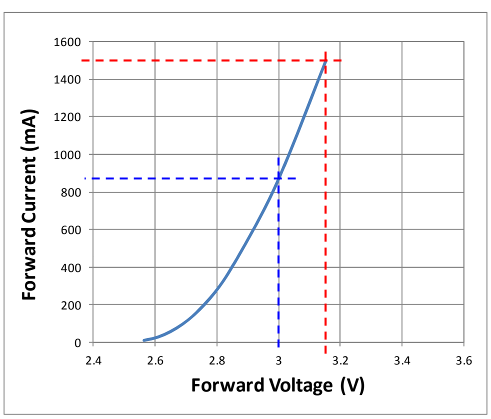
  - **Electrical**
  - Optical
- Building luminaries
  - A19 Bulb
  - Street Light

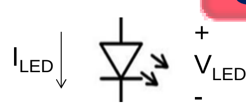
Electrical – Current or Voltage Drivers?

Level 2

Level 3

- Recap





At 3.00V, I_{LED} = 870mA

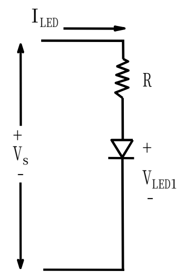
At 3.15V, I_{LED} = 1500mA

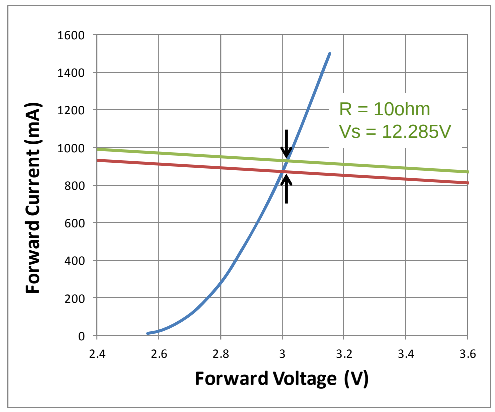
5% $\Delta V_{LED} \rightarrow \Delta I_{LED}$ 72%!

Consideration for Voltage Driver Design

$$V_S = I_{LED} R + V_{LED1}$$

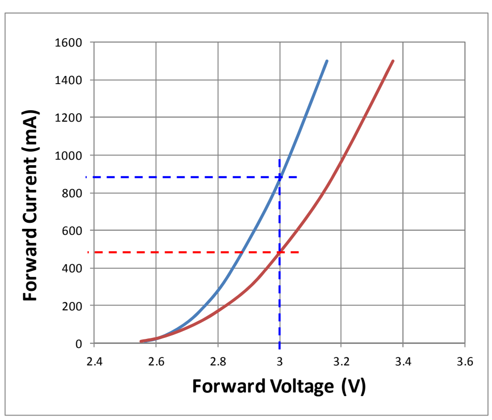
$$I_{LED1} = \frac{V_S - V_{LED1}}{R}$$

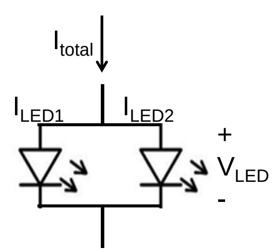




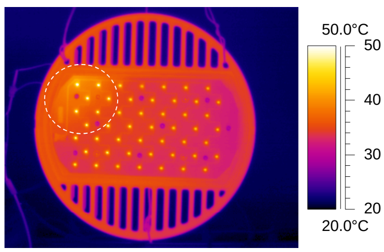
- If R is large, I_{LED} is insenstive to V_s fluctuation Disadvantage: very inefficient!

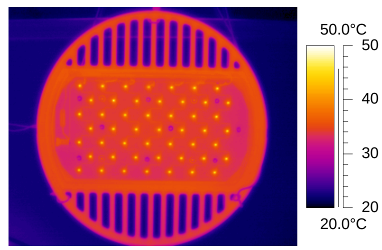
Electrical – Series or Parallel?





Electrical Power Distribution – PCB Copper Trace Layout





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Summary

- LEDs are best driven by current source
- Connecting LEDs in parallel is more challenging than in series
- In high current operation, PCB copper trace width and length need to be considered

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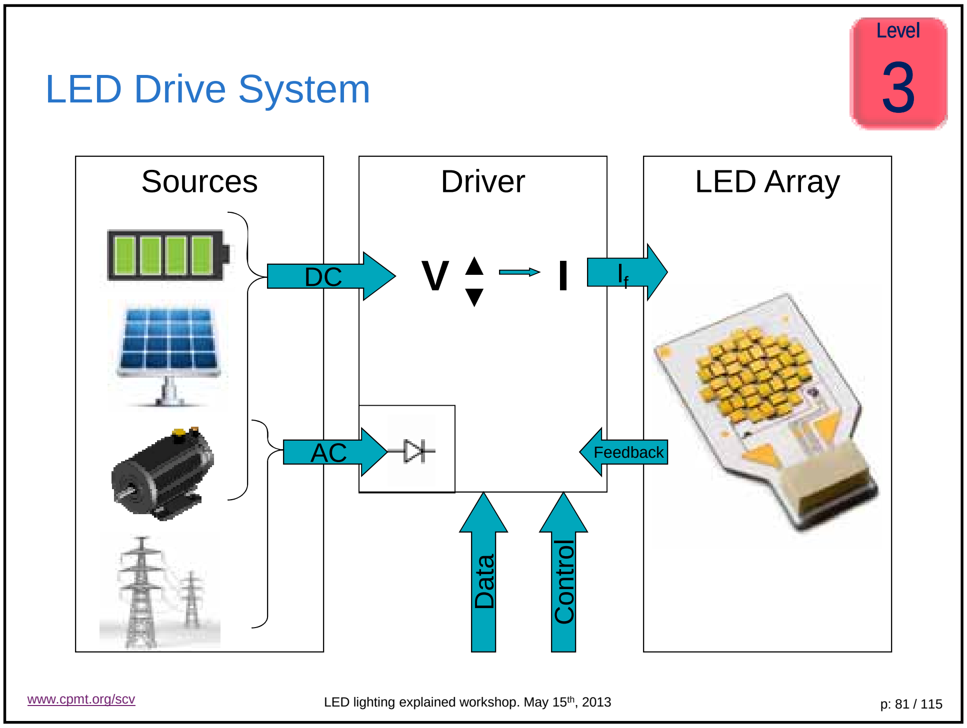
Level
3
LED Drive System
Sources
Driver
LED Array
DC
V
I
I_f
AC
Feedback
Data
Control
www.cpmt.org/scv
LED lighting explained workshop. May 15th, 2013
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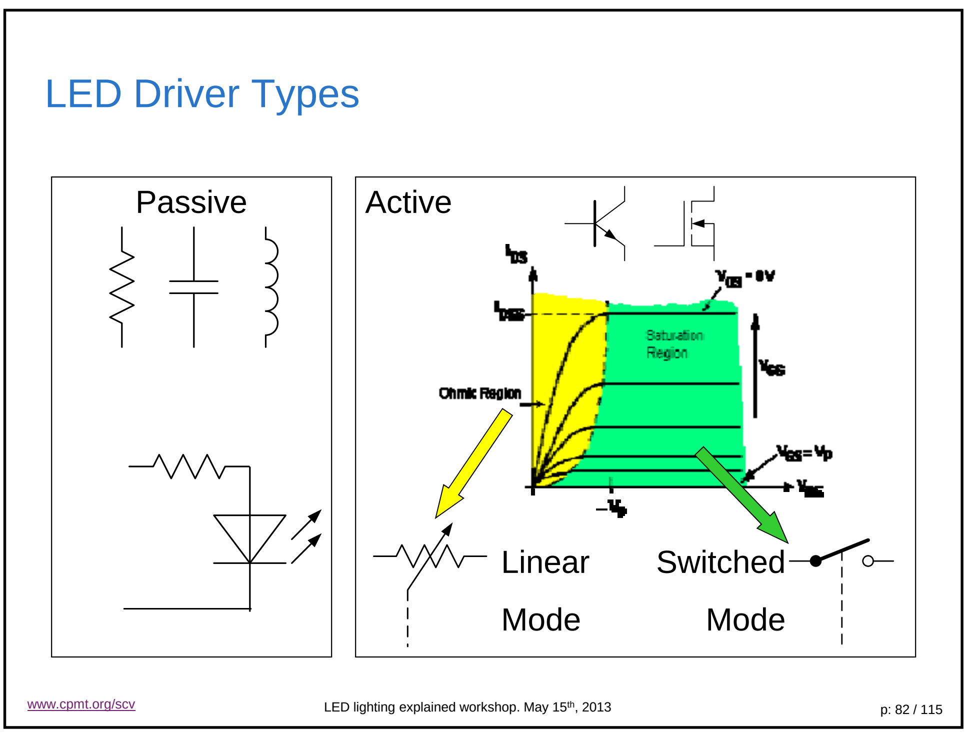
LED Driver Types
Passive
Active
Saturation Region
Ohmic Region
Linear Mode
Switched Mode
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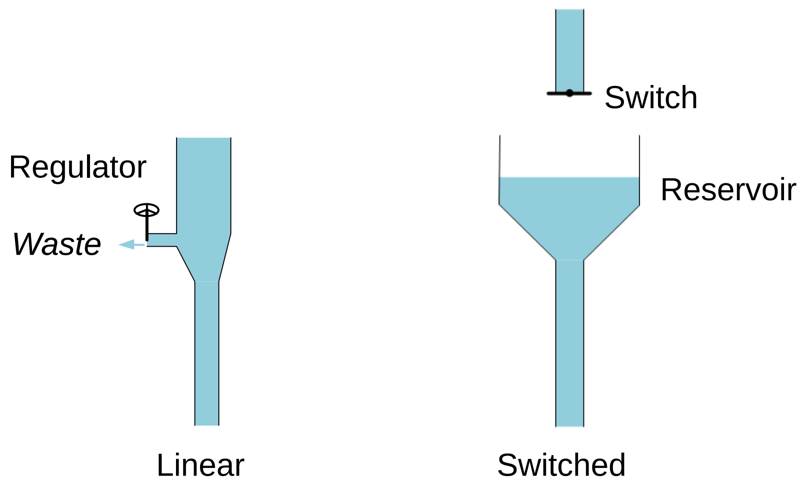
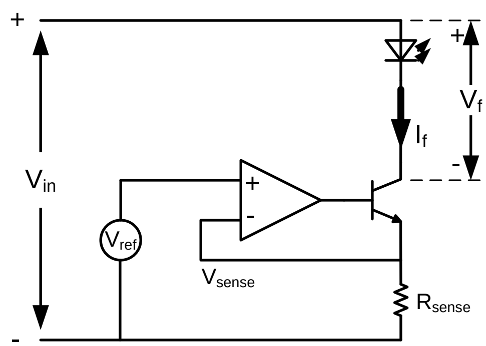
Switch vs Linear Analogy



Linear Regulator (Constant Current Regulator, CCR)



$$I = \frac{V_{ref}}{R_{sense}}$$

$$P_{in} = V_{in} \cdot I_f$$

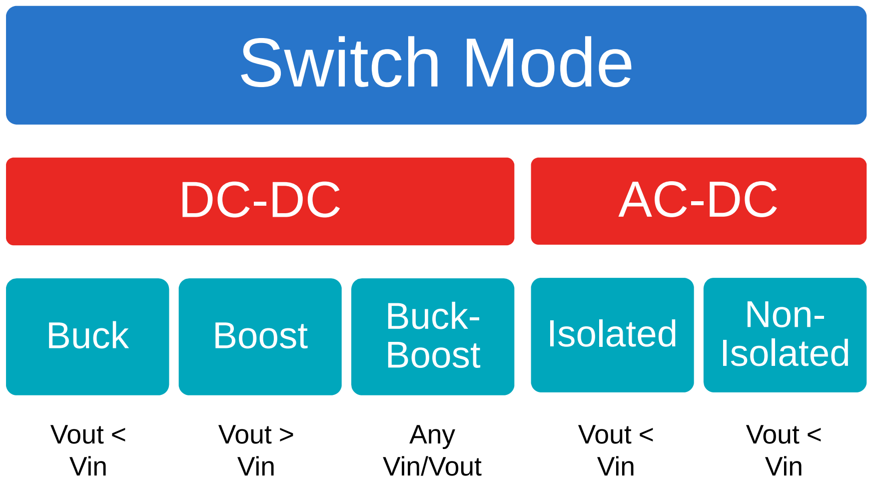
$$P_{out} = V_f \cdot I_f$$

$$\eta = \frac{P_{out}}{P_{in}}$$

Typical efficiency ~ 70%

Typical current variation ± 5% with V_{in} ±10%

Switch Mode Regulators



Comparison

	Linear	Switch Mode
Cost	Cheap	Expensive
EMC	No issue	Potential
Circuitry	Simple	Complicated
Efficiency	Low (~70%)	High (75% .. 93%)
Size & Weight	Larger and heavier	Smaller and lighter

Other Electrical Considerations

- Transients
- Switching
- Brownout
- Lightning
- Dimming (resistor vs triac control PWM)
- Hipot testing
- Power factor

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  - Street Light

Optics

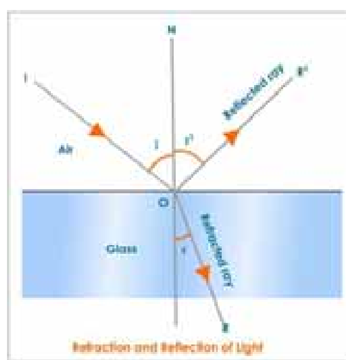
Level
3





Basic Principles

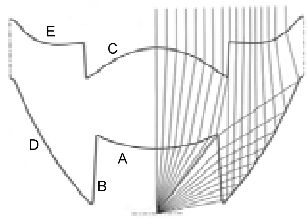
- Refraction (Snell's law)
- Reflection
- Absorption and Transmission



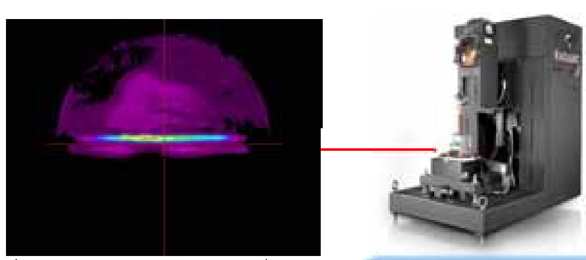
Optical Design

1) Optical software simulation such as ASAP, LightTools, Zemax, TracePro, Photopia

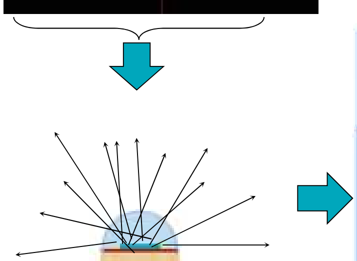
2) LED light source
   - Optical model creation using the above optical sofware
   - Measured rayset

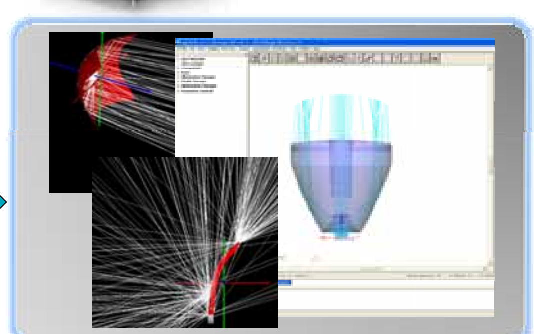


Rayset



Source imaging / Near-field goniophotometer
- Radiant Zemax
- TechnoTeam





Optics Consideration

- Optical efficiency ~85%-90%
- LED light source distribution
- LED apparent source size
- Final optics size
- Material selection (polycarbonate, PMMA, glass)
- Fire safety consideration (UL)

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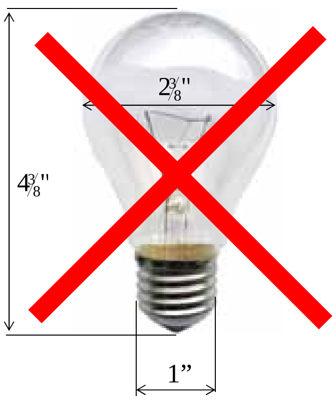
Building a Lamp System or Luminaire – A19 Bulb

Level 3



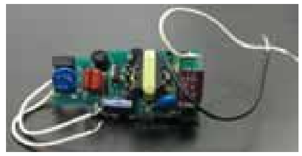
- Cost
- Efficiency

A19 LED Bulb Assembly

Level 3

A19 Sub-Components

Plastic housing, E26 screw & electrical contact pin

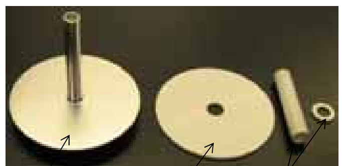


LED driver

LED array board (shown without LUXEON LEDs and thermal interface material)

LED white reflector sheet

Heat sink



Top metal bulb cover

Top reflector sheet

White reflector plastic tube & washer

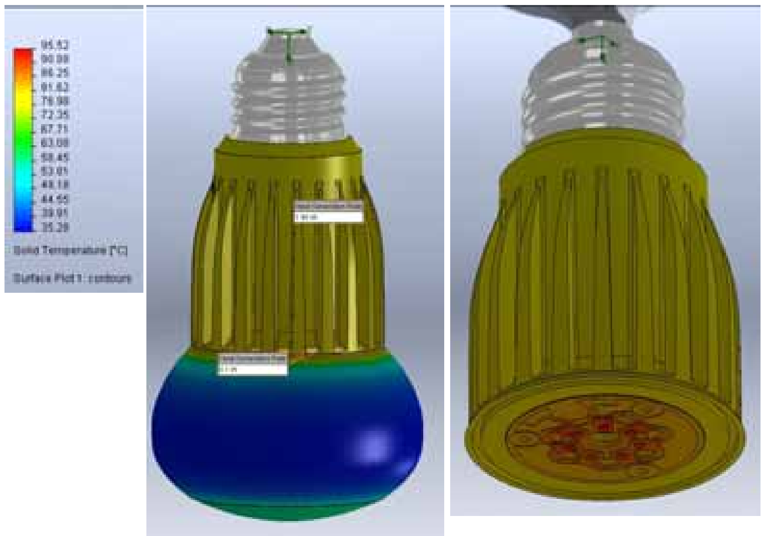
bulb

Not shown or provided are glues/adhesives, potting material, solder and screws

Technical Evaluation

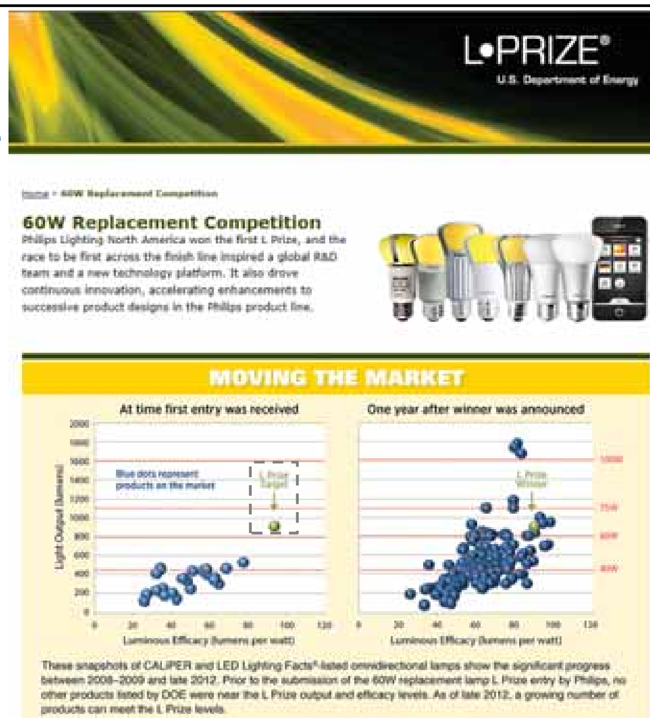
	Energy Star Requirement	60W
LED Count	-	7up LXH8-PW30
CCT	ANSI	3000K
CRI	80 min	80 min
Lumens (min)	800	800
Lm/W	55	58
Beam Angle	+/-135 within 20% of avg	Yes
Lumen Maintenance	>70% (L70) 25Khrs	>70% (L70) 25Khrs
Input Voltage	-	110 VAC
Bulb Power	-	13.7W
Current	-	575 mA
Driver	-	Marvell
Driver efficiency	-	>85%
Power Factor	>0.7	>0.9

Thermal

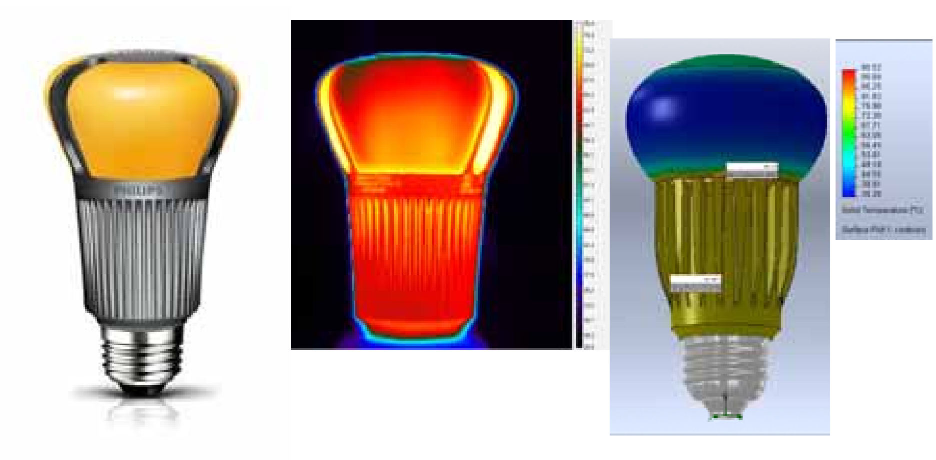


Philips A19 60W L-Prize

- InGaN chip WPE improvement
- Remote phosphor
- Thermal design



L-Prize vs Concept A19 (60W) Bulb Thermal Comparison



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Level 4

Street Light

Level 4

- Regional standards
- Lighting distribution, light pollution
- Maintenance
- Power efficiency
- Cost
- Lighting control

Los Angeles before LED Retrofit project (2008)

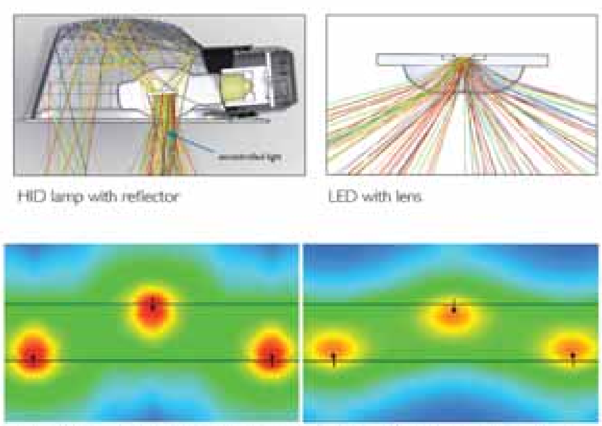
Photo credit: City of Los Angeles, taken from Mount Wilson

Los Angeles after LED Retrofit project (2012)

- 98,000 of the cities 210,000 streetlights moved to LED

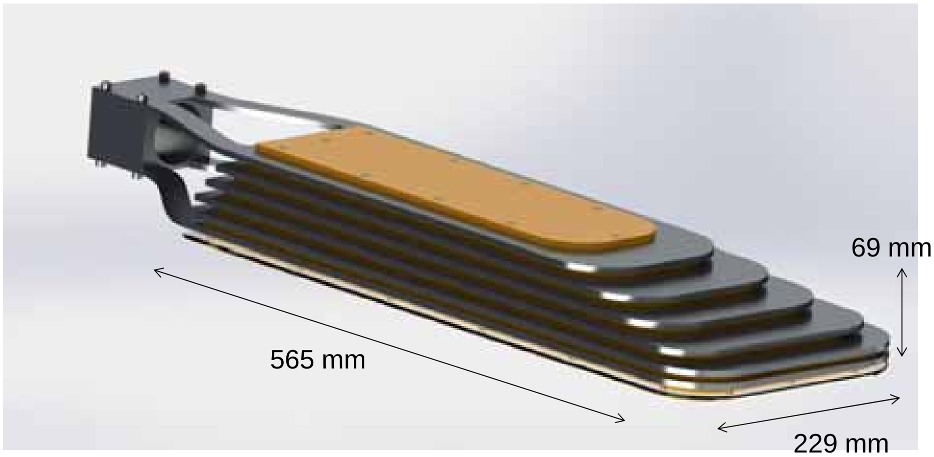
Photo credit: City of Los Angeles, taken from Mount Wilson

LEDs Enable Superior Light Shaping Capability



The HPS luminaire (left) concentrates a lot of light below and behind the pole. The LED luminaire provides more uniform lighting on the roadway while minimizing light trespass.

Design Concept



www.cpmt.org/scv LED lighting explained workshop. May 15th, 2013 p: 107 / 115

Design Concept

- 12 LUXEON M  and Ledil Strada optic
- PMMA Coverplate

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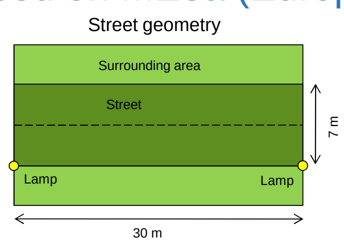
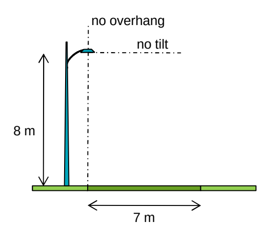
Cross section

- Room for the Advance 150W outdoor driver
- Hollow sections to save weight

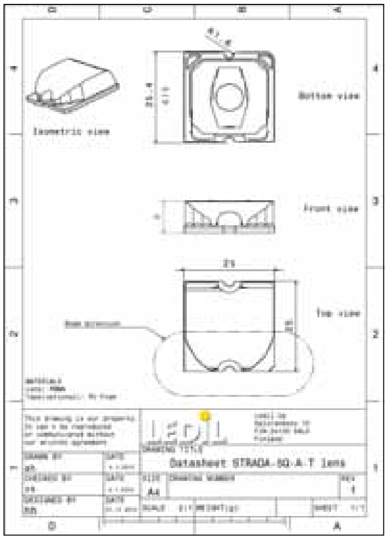
Street Geometry and Performance Requirements Based on ME3a (European)



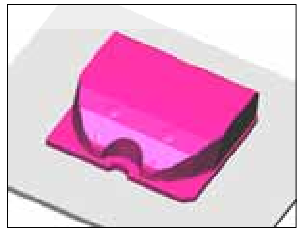


Street geometry:		Lighting class: ME3a	
- Road pavement:	R3 classification	- Average luminance (Lavg):	1 Cd/m2
- Pole height:	8 meter	- Overall uniformity (Uo):	> 0.4
- Pole distance:	30 meter	- Longitudinal uniformity (Ul):	> 0.6
- Street width:	7 meter	- Threshold increment (TI):	< 15%
- Number of lanes:	2	- Surround ratio (SR):	~ 0.5
- Lamp overhang:	0 meter		
- Lamp tilt angle:	0 degrees	- lumen maintenance = 0.8	
- Placement:	Single sided (unilateral)		

The Optics: Ledil Strada-SQ-A-T for LUXEON M



Secondary lens for LUXEON M
Type II intensity distribution



Product	Light distribution	Application / notes	Schedule
Strada-SQ-A-T	asymmetric	Street lighting IESNA Type II for narrow roads	End of February
Strada-SQ-T-DWC	asymmetric	Street lighting IESNA Type III for normal roads	End of March

Summary of System Characteristics Performance (20°C Ambient)

Parameters	Performance
Drive current	700mA
Total light output	10,756 lumens
Total LED power	95.7W
Lamp system efficacy	86.5 lm/W
Driver efficiency	85%
Optical efficiency luminaire	90%
Junction temperature	87 C
Heat sink temperature	50 C

Street performance: Meets the ME3a street light requirements.

The End
Questions?

PHILIPS