

LED Lighting Explained Workshop, May 15th 2013

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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

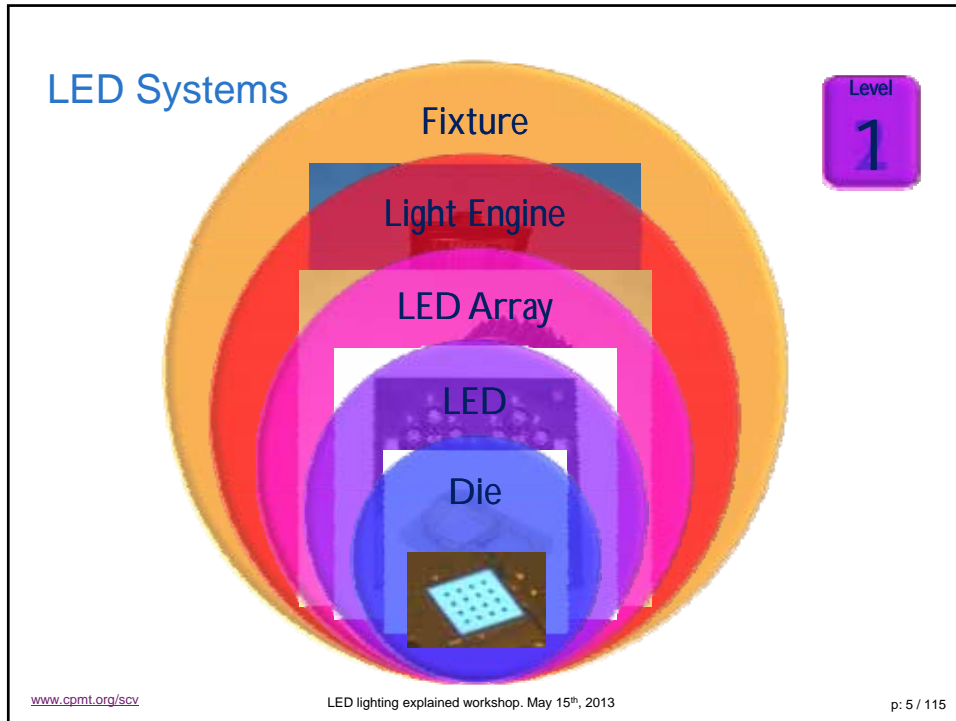
Evolution of Lighting

- 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



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Level	Level
0	1
Level	Level
2	3
Level	Level
3	4

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p: 6 / 115

Simplified LED operation

The diagram shows a cross-section of an LED chip. A green arrow labeled "Electrons" points into the chip from the left. From the top of the chip, a blue arrow labeled "Photons" points upwards. From the bottom of the chip, a red arrow labeled "Heat" points downwards. To the right of the chip, the efficiency equation is given as $\eta_o = \frac{N_{ph}}{N_e}$. A blue box in the top right corner contains the text "Level 0".

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

Level 0

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Photon Energy and Wavelength

The diagram features a blue sine wave representing a photon. A horizontal line is drawn through the wave. A double-headed arrow below the wave indicates the wavelength, labeled with the Greek letter lambda (λ). Below the wave is a color spectrum bar with labels: V (Violet), B (Blue), G (Green), Y (Yellow), O (Orange), R (Red), and I (Infrared). Below the spectrum bar, a blue arrow points left towards the text "Higher photon energy", and a red arrow points right towards the text "Lower photon energy". To the right of the wave, the energy equation is given as $E_{ph} = \frac{hc}{\lambda}$. A blue box in the top right corner contains the text "Level 0".

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

Level 0

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LED Illustration

Level
0

p-layer n-layer

“Bandgap E_g ”

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

junction

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LED Material System - AlInGaP

Level
0

Periodic Table of the Elements

AlInGaP

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LED Material System - InGaN

Level
0

Periodic Table of the Elements

InGaN



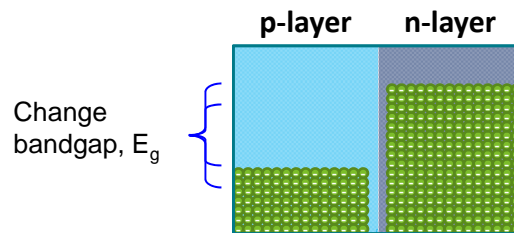
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p: 11 / 115

How Different Colors Are Produced?

Level
0



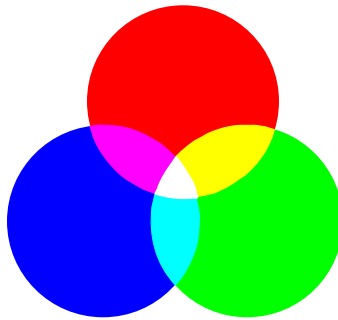
- Aluminum Indium Gallium Phosphide, $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{In}_{0.5}\text{P}$
- Indium Gallium Nitride, $\text{In}_x\text{Ga}_{1-x}\text{N}$

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p: 12 / 115

What About White?



- Mix RGB LEDs
- Add phosphor material to blue LED

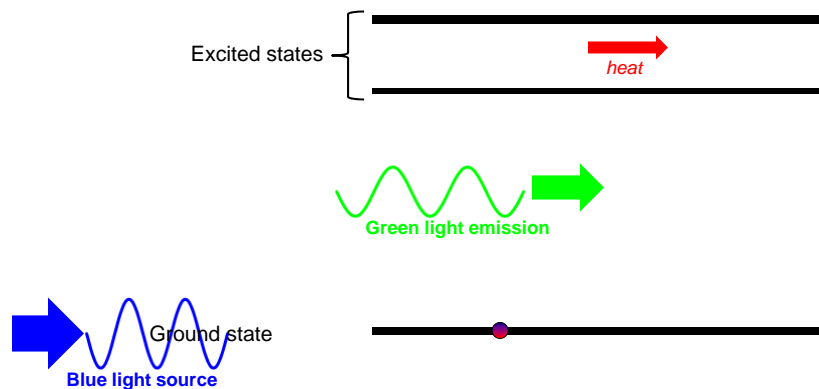
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p: 13 / 115

Phosphor – Basic Physics

Electroluminescence vs photoluminescence



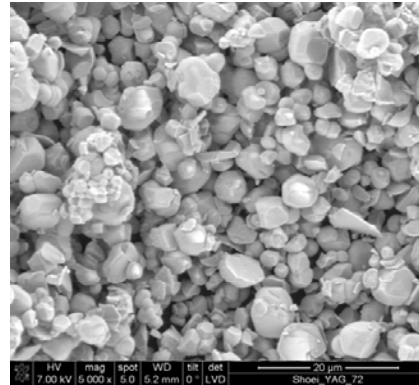
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p: 14 / 115

Phosphor Materials

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



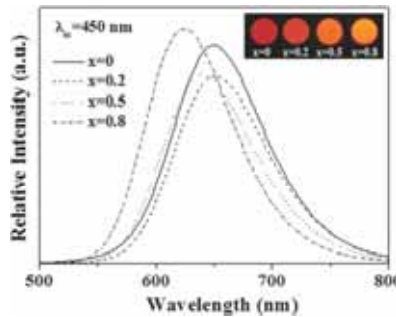
Example of red phosphor
- $(\text{Sr}_x\text{Ca}_{1-x})\text{AlSiN}_3:\text{Eu}$

"Rare" Earth Metals

<p>21 Sc Scandium 44.955912</p> <p>39 Y Yttrium 88.90585</p>											<p>63 Eu Europium 151.964</p>		<p>64 Gd Gadolinium 157.25</p>		<p>71 Lu Lutetium 174.9668</p>							
<p>For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.</p>																						
<p>Periodic Table Design & Website Copyright © 1997 Advanced Science Platform.com Ltd (updated Jan 1, 2011)</p>																						
57-71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu								
(138.905)	(140.127)	(140.908)	(144.242)	(144.913)	(150.36)	(151.964)	(157.25)	(158.925)	(174.966)	(162.503)	(167.259)	(168.934)	(173.054)	(174.9668)								
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr								
(227)	(232.038)	(231.036)	(238.029)	(237.048)	(244.041)	(243.061)	(247.073)	(247.073)	(251.108)	(252.083)	(255.106)	(259.106)	(259.106)	(260.106)								

Example of Phosphor Emission Spectra Control

Spectra of $(\text{Sr}_x\text{Ca}_{1-x})\text{AlSiN}_3:\text{Eu}$ 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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p: 17 / 115

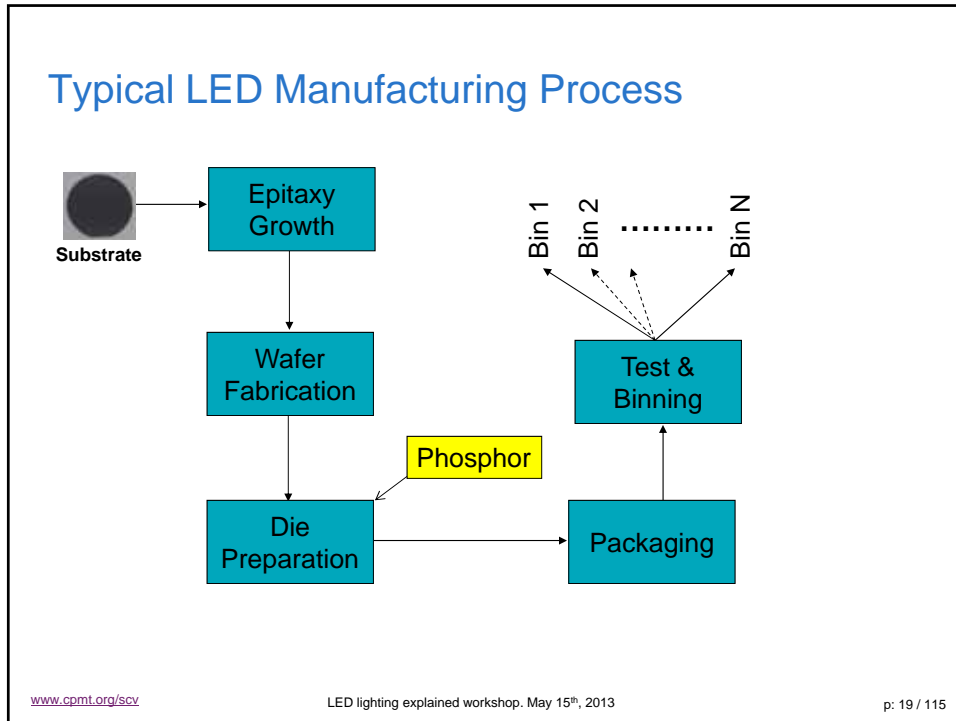
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p: 18 / 115



Epitaxy Growth & Wafer Fabrication

n-contact
dielectric
p-contact
InGaN Active Layer
Sapphire Substrate

n-GaN
p-GaN

**Wafer
Fabrication**

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Die Preparation

Level
0

- Testing
- Singulation
- Visual Insp

**Die
Preparation**

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Level 1 Packaging

Level 1

The diagram illustrates the Level 1 packaging process. It shows a central LED chip with three arrows originating from it: a green arrow labeled 'Electrical contacts' pointing left, a blue arrow labeled 'Light extraction' pointing up and to the right, and a red arrow labeled 'Heat extraction' pointing down and to the right. Below the chip, the text 'Mechanical support and protection' is written. To the right of the diagram is a photograph of a packaged LED chip on a substrate.

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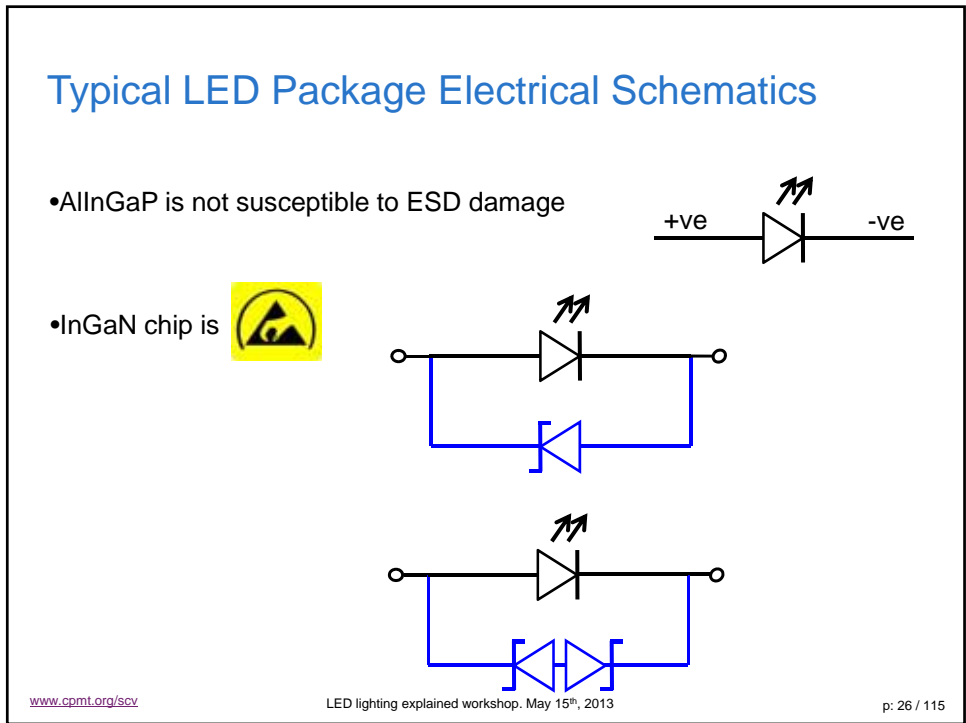
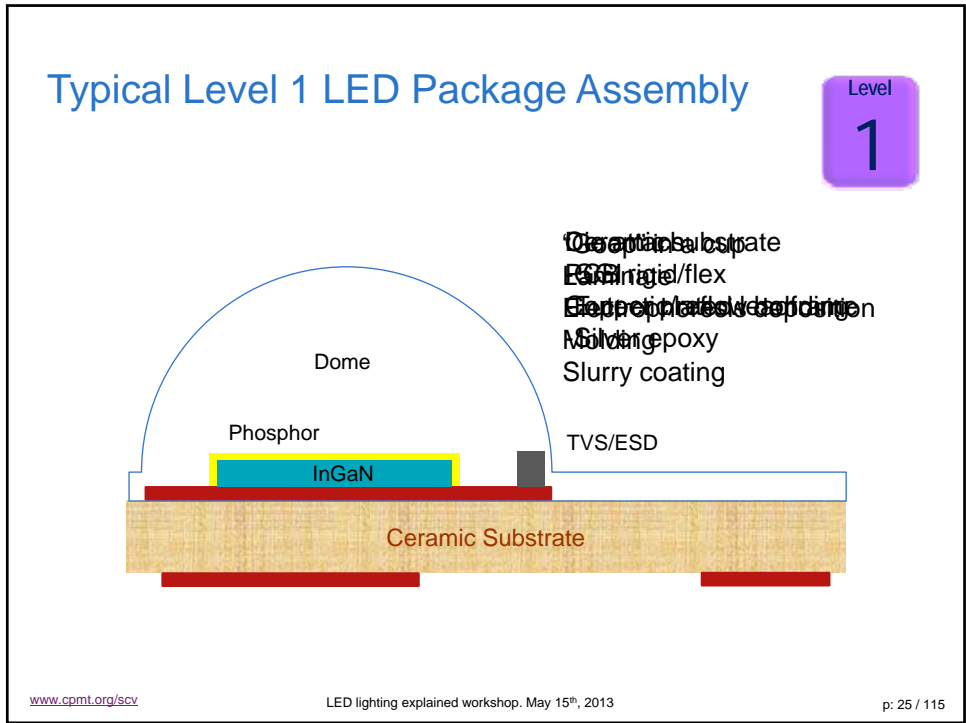
Level 1 Packaging

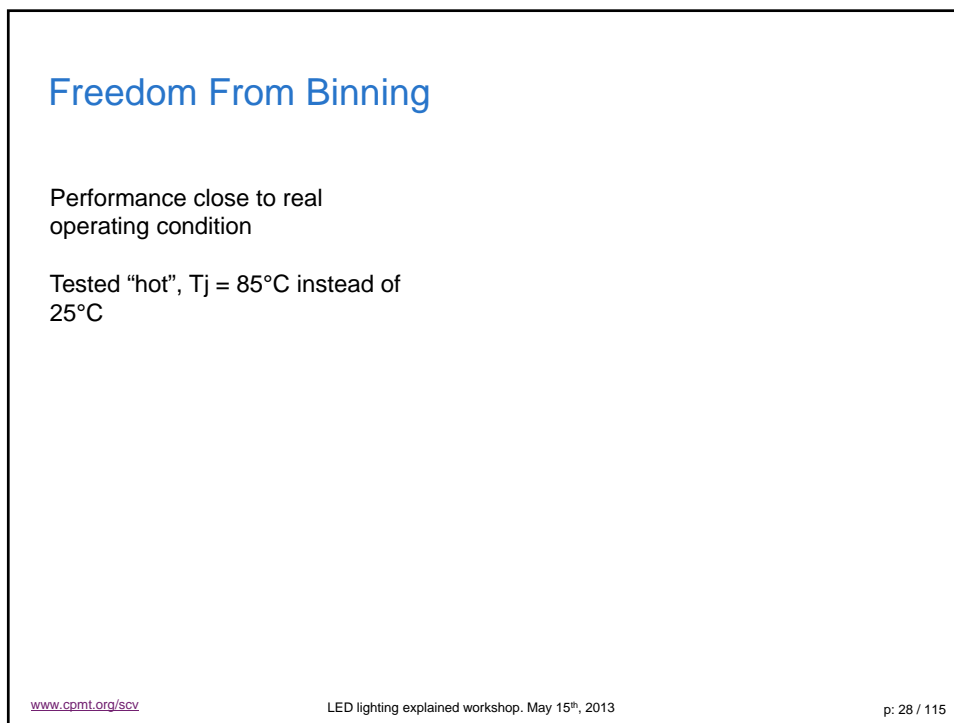
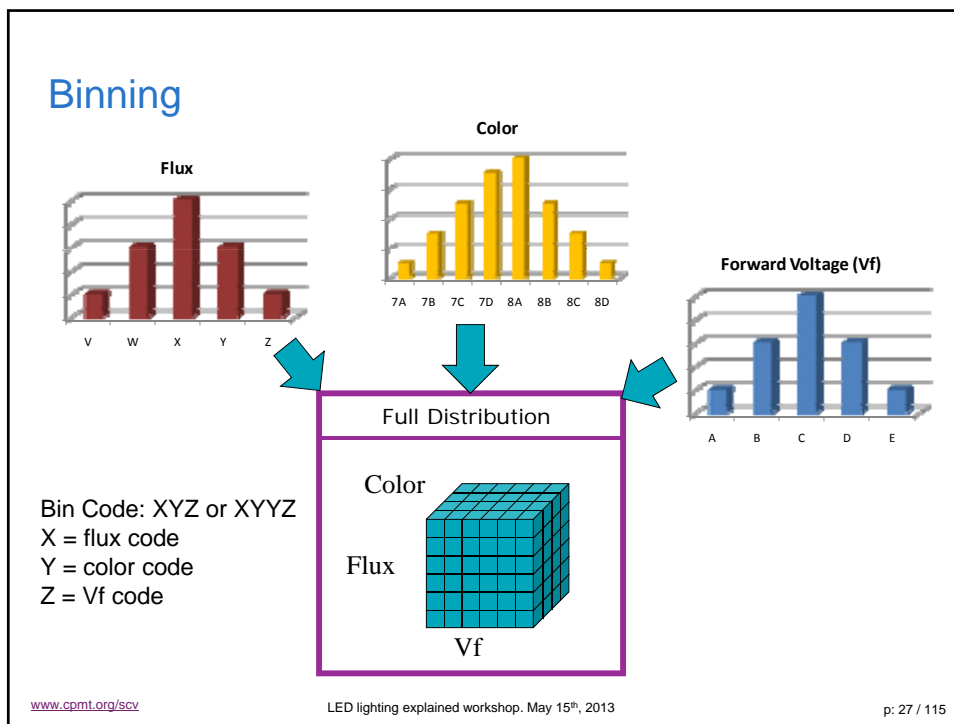
Level 1

- Low Power (~0.1W) to Mid Power (~0.5W)
- High Power (> 1W)

This slide displays a variety of LED packages. The top row shows five examples of low to mid-power packages: five small through-hole LEDs, a small surface-mount LED, a rectangular surface-mount LED, a square surface-mount LED, and a larger square surface-mount LED with a metal heat sink. The bottom row shows high-power packages, including a large circular package with a heat sink, a square package with a heat sink, a large square package with a heat sink, and a row of four square packages of varying sizes, all featuring yellow LED chips and heat management structures.

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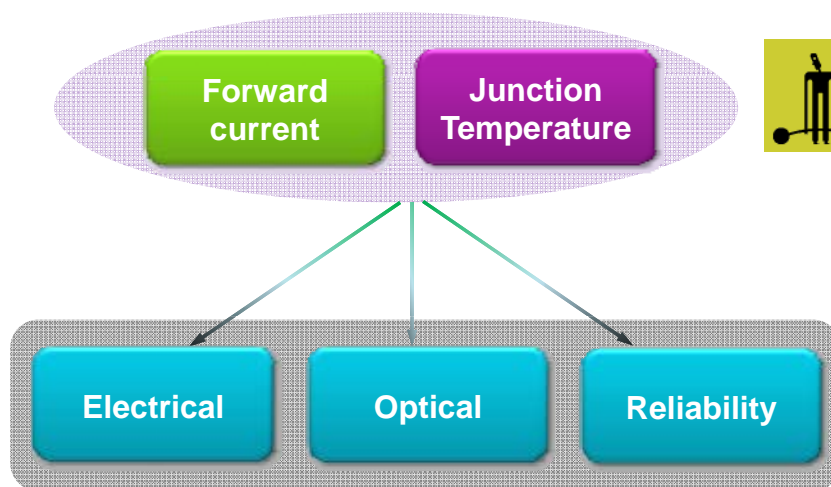
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p: 29 / 115

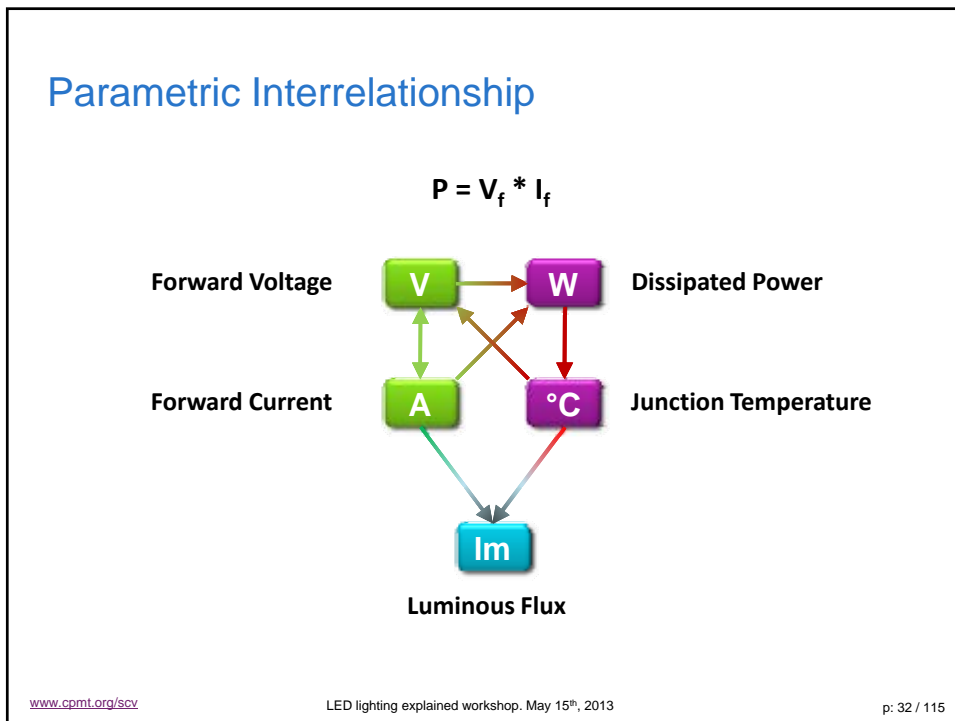
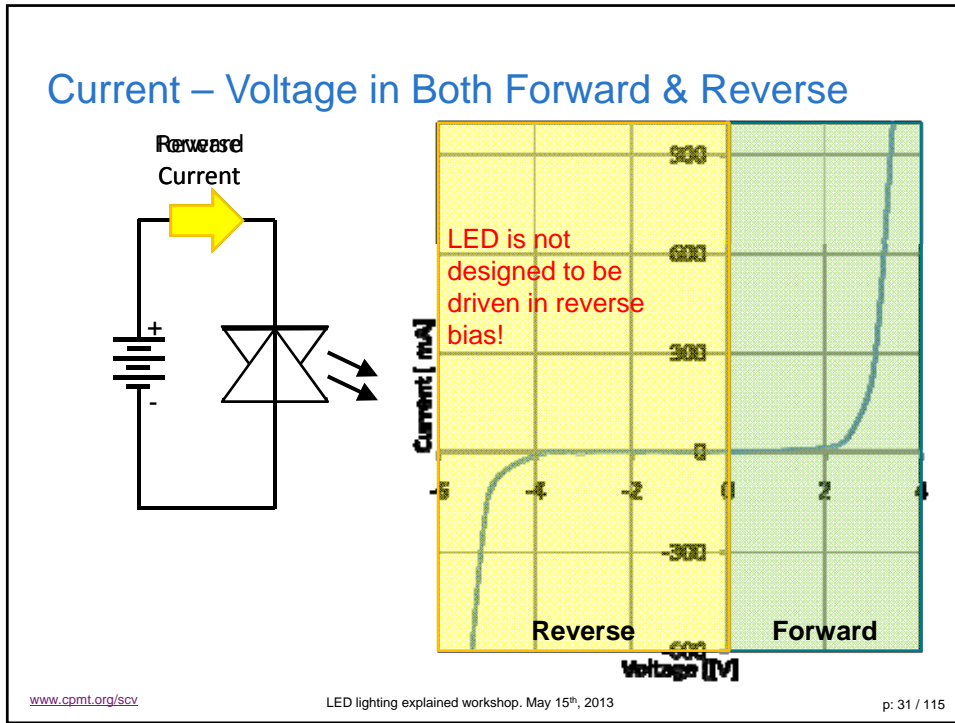
LED Performance Characteristics



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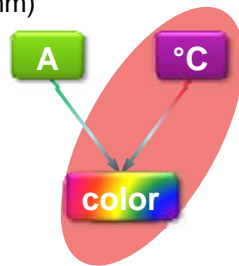
p: 30 / 115



What About Color?

Color parameters:

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



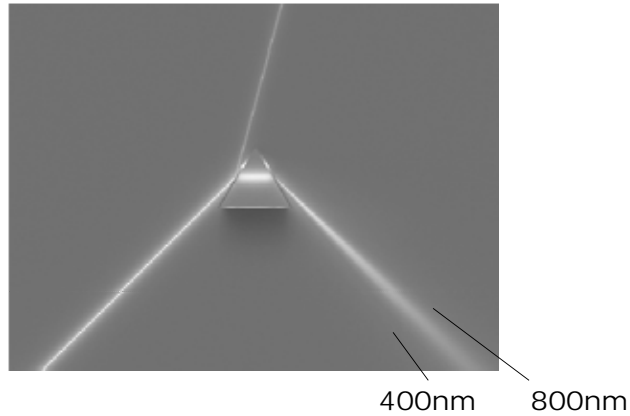
$$\frac{\Delta\lambda_{peak(dom)}}{\Delta T} = +0.5 \text{ nmV}/^{\circ}\text{C}$$

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There is no color in physics class

No Laws or Theorems

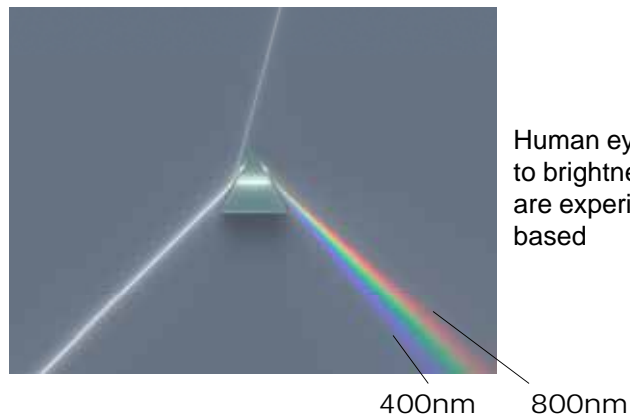


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p: 35 / 115

It's all in your head ... Human perception



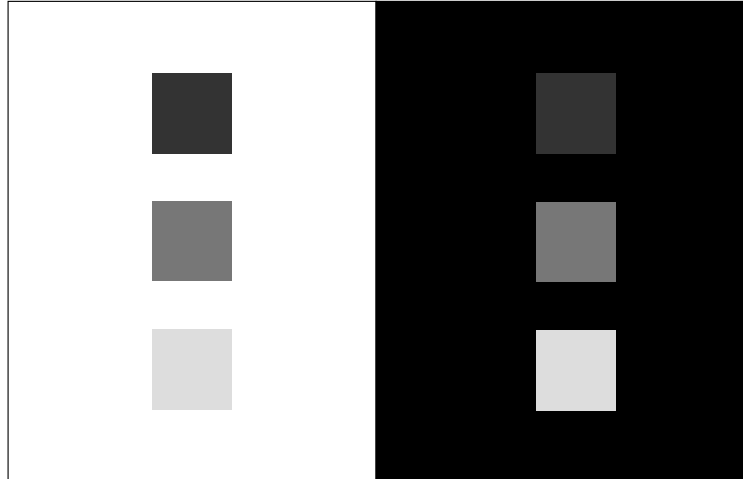
Human eyes response
to brightness and color
are experimentally
based

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p: 36 / 115

Fun Stuff – Eye Tricks

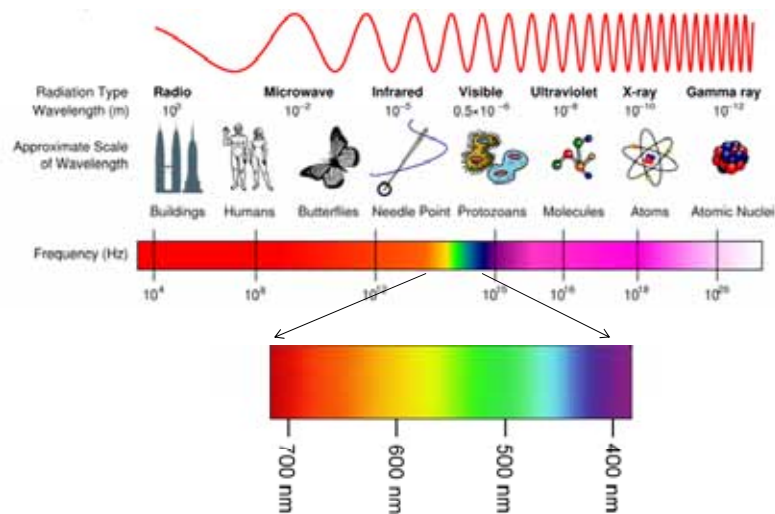


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p: 37 / 115

Visible Radio

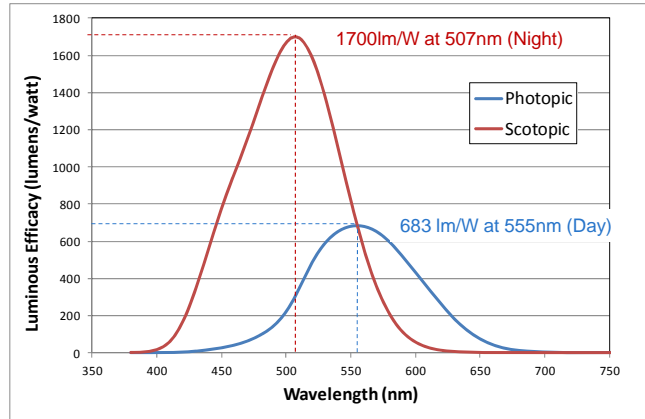


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p: 38 / 115

Photopic Scotopic Mesopic

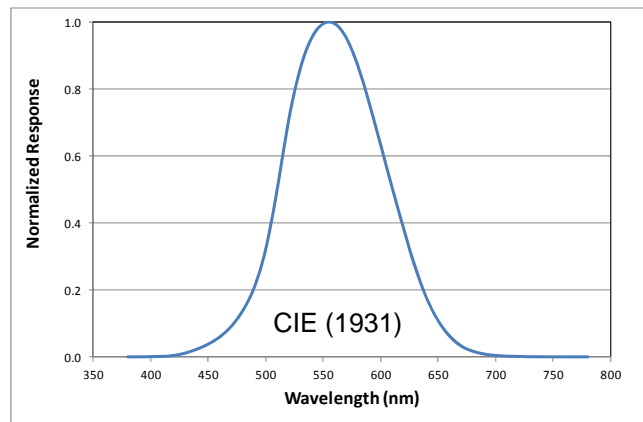


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p: 39 / 115

Photopic Eye Response (Luminosity Function, $V(\lambda)$) as Defined by CIE 1931

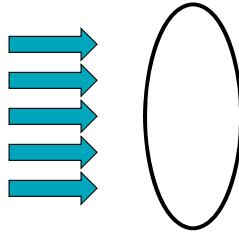


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p: 40 / 115

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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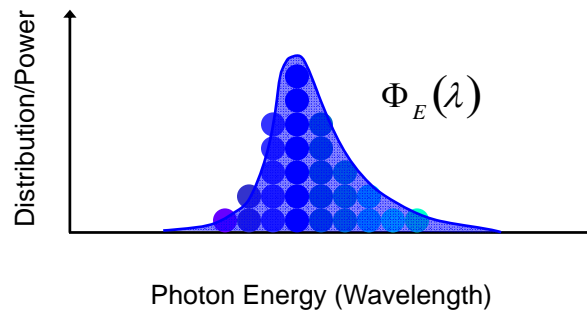
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p: 41 / 115

Flux Calculation

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

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

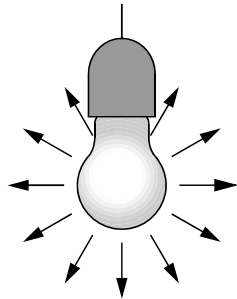


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p: 42 / 115

Flux Calculation (continue)



Photometric Flux

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

Radiometric Flux

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

1 W Radiant Flux at 555 nm = 683 lumens

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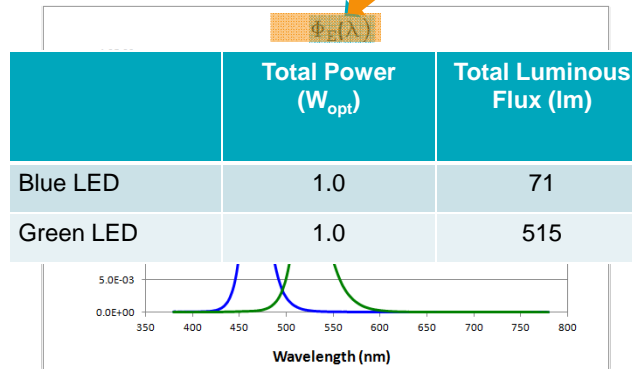
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p: 43 / 115

Example: Photometric Flux for Blue and Green LEDs

- Blue and Green LEDs with one watt of optical power

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



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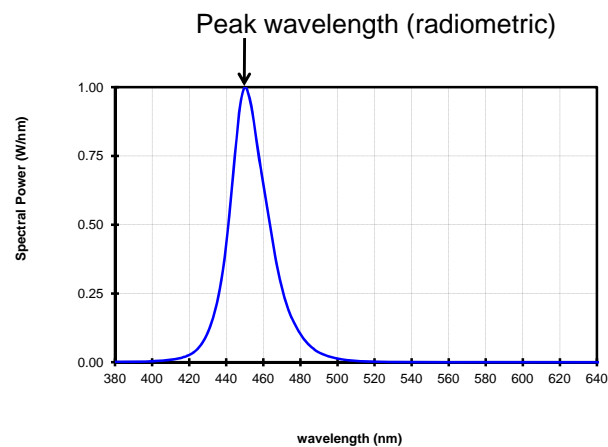
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p: 44 / 115

Color Measurements

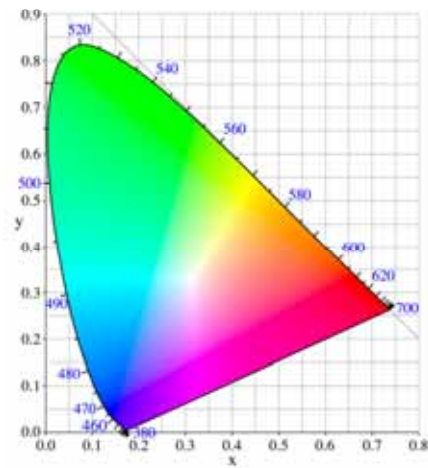
- RECALL...
 - Peak wavelength (nm)
 - Color points (x, y) in CIE 1931 color space or in (u', v') CIE 1976 color space
 - Dominant wavelength (nm)
 - Let's define these parameters

Peak Wavelength



Color Points

- Create color space

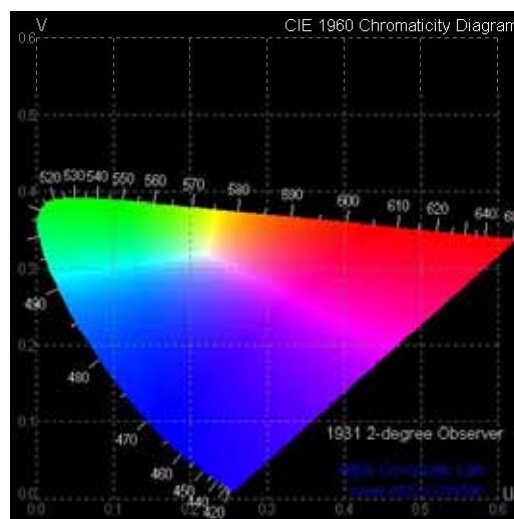


CIE 1931

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p: 47 / 115

Another Color Space



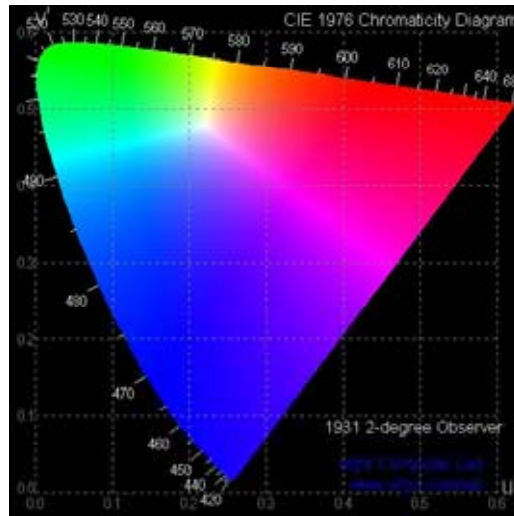
CIE 1960

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p: 48 / 115

Or Another One?



CIE 1976

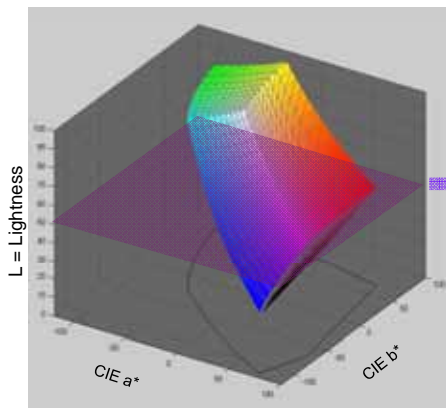
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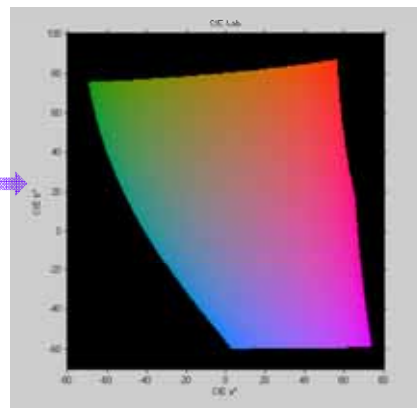
p: 49 / 115

Last One? ... and many more.....

CIE 1976 L*a*b*



Slice at L=50



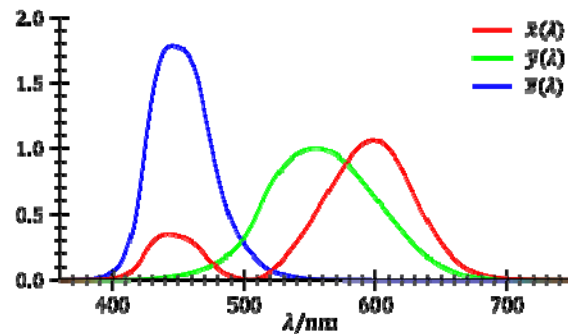
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p: 50 / 115

CIE 1931 Color Matching Functions

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



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p: 51 / 115

CIE 1931 Color Definition

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

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

Unit for X, Y and Z is lumen

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p: 52 / 115

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

$$x + y + z = 1 \longrightarrow (x, y) \text{ chromaticity color points in CIE 1931 color space}$$

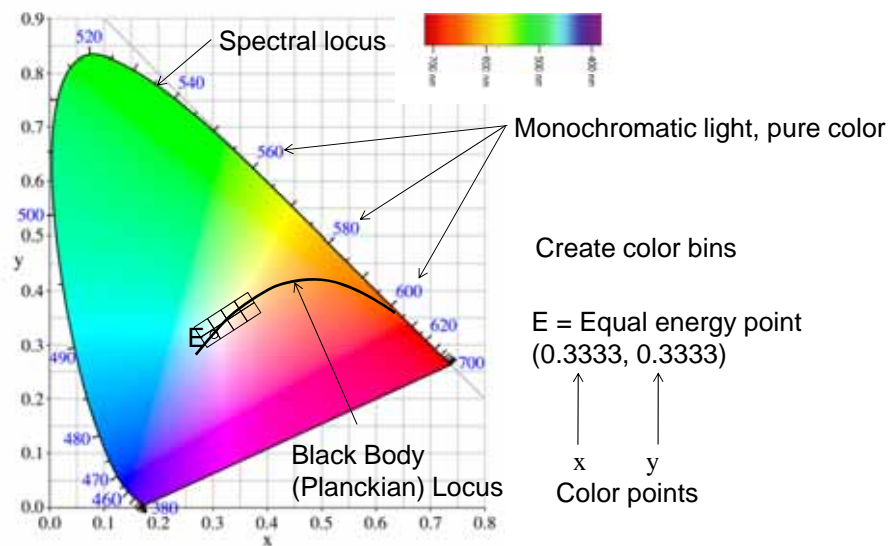
- For more details, see “Wyszecki & Stiles (Wiley Series), *Color Science: Concepts and Methods, Quantitative Data and Formulae*”

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p: 53 / 115

The CIE 1931 xyY Color Space



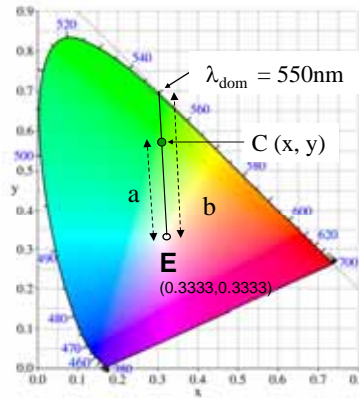
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p: 54 / 115

Now We Can Finish of Dominant Wavelength Color Definition

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

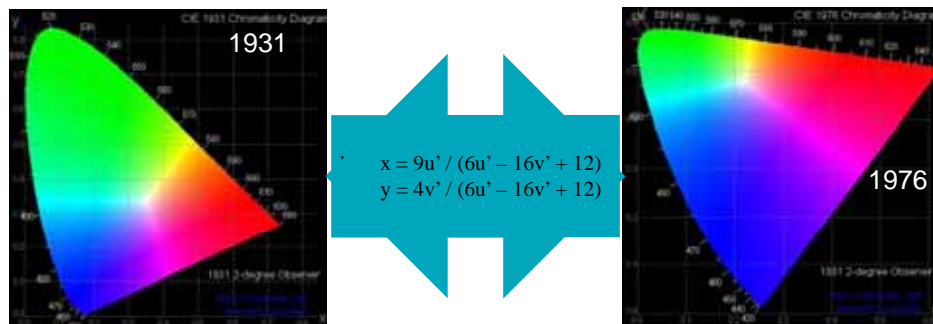


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p: 55 / 115

CIE 1931 / CIE 1976 Color Space Conversion






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p: 56 / 115

Recap....

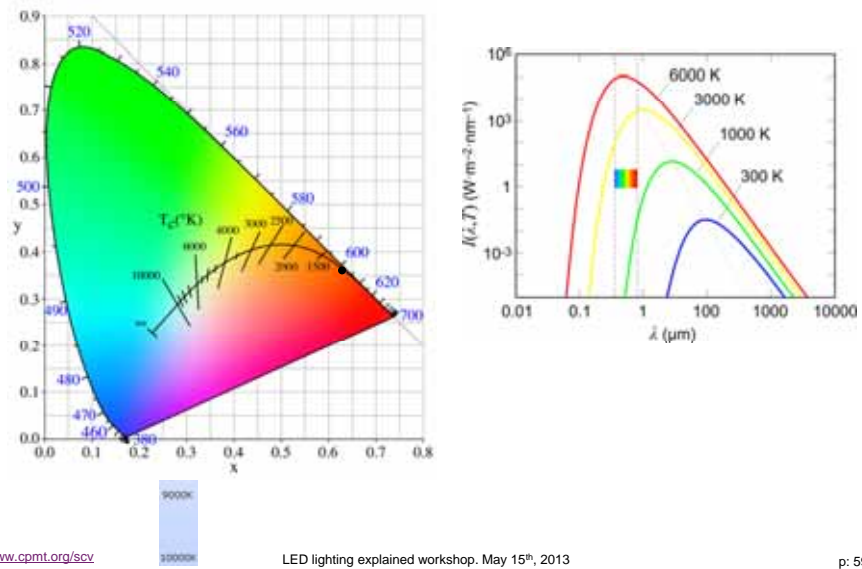
- Peak wavelength (nm) 
- Color points (x, y) in CIE 1931 color space 
- Dominant wavelength (nm) 

Other LED parameters to describe “white” color?

White Color

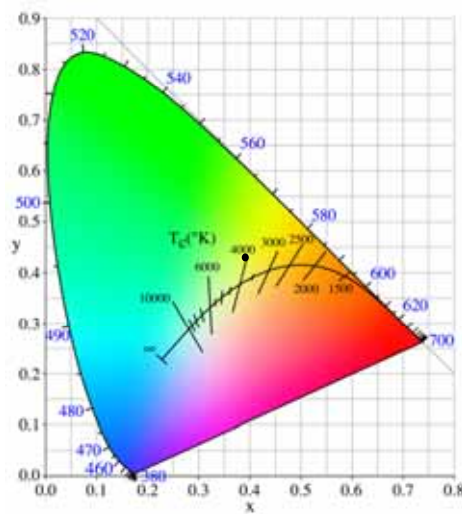
- Correlated Color Temperature (CCT, in K)
- Color Rendering Index (CRI, dimensionless, between 0 to 100)

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



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p: 61 / 115

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p: 62 / 115

What to Consider When Building a LED System?



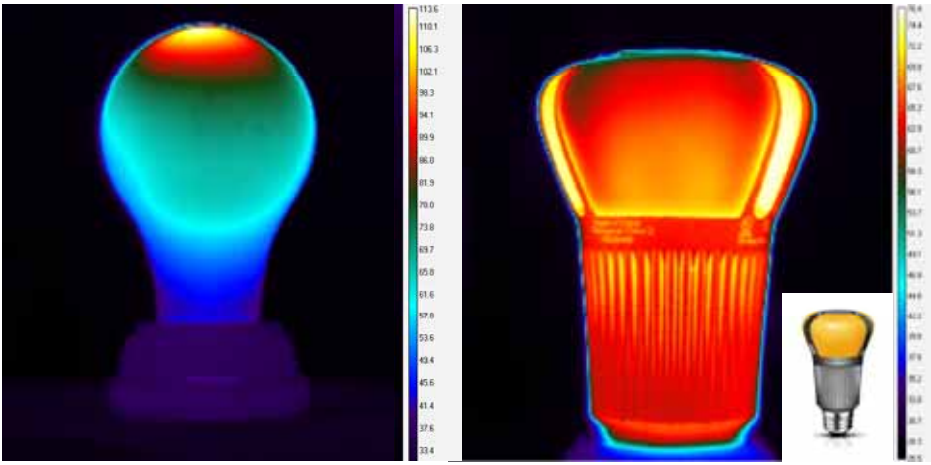
- 1) Thermal
- 2) Electrical
- 3) Optics

Level 2

Level 3

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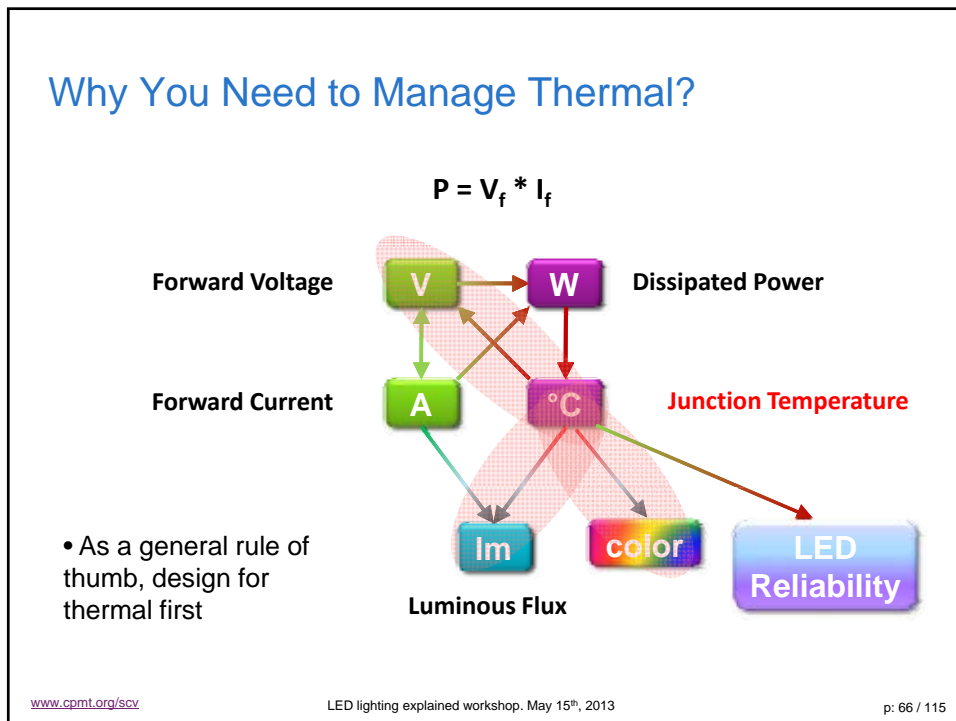
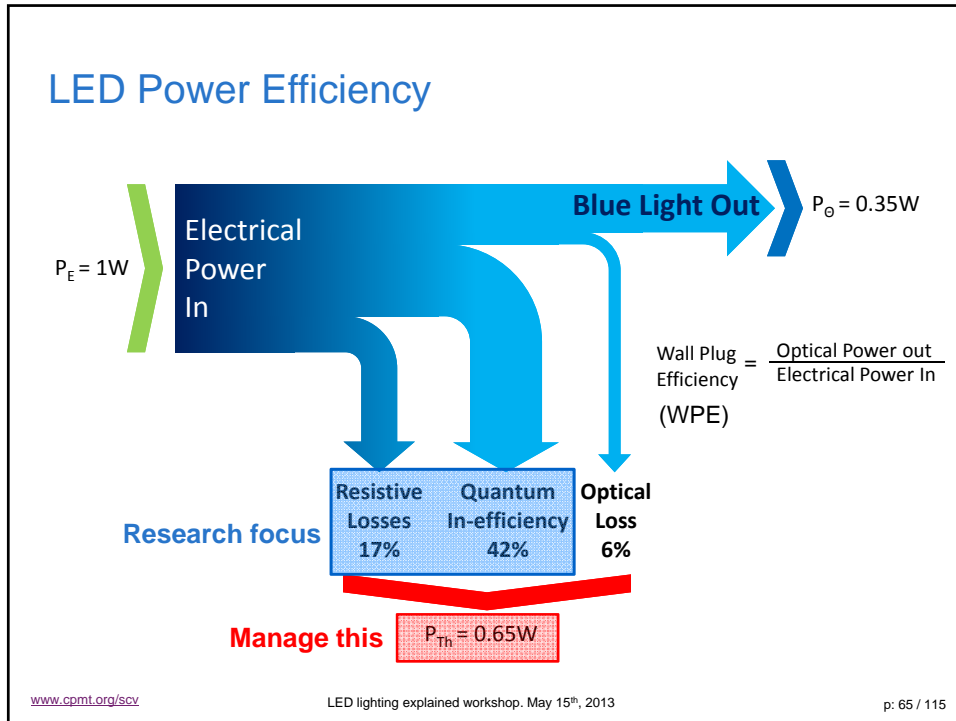
Thermal – Tungsten versus LED Bulb



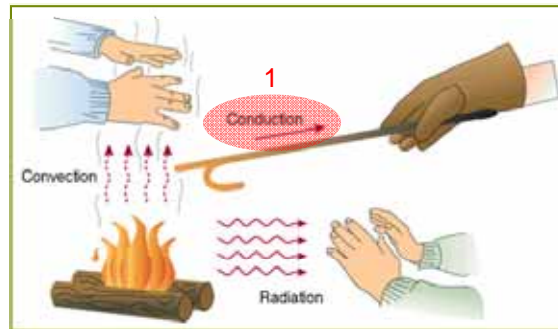
40 Watt Incandescent

Philips 60W L Prize

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Keep LED Junction Temperature Low. How?



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p: 67 / 115

Thermal Resistance (Rth)

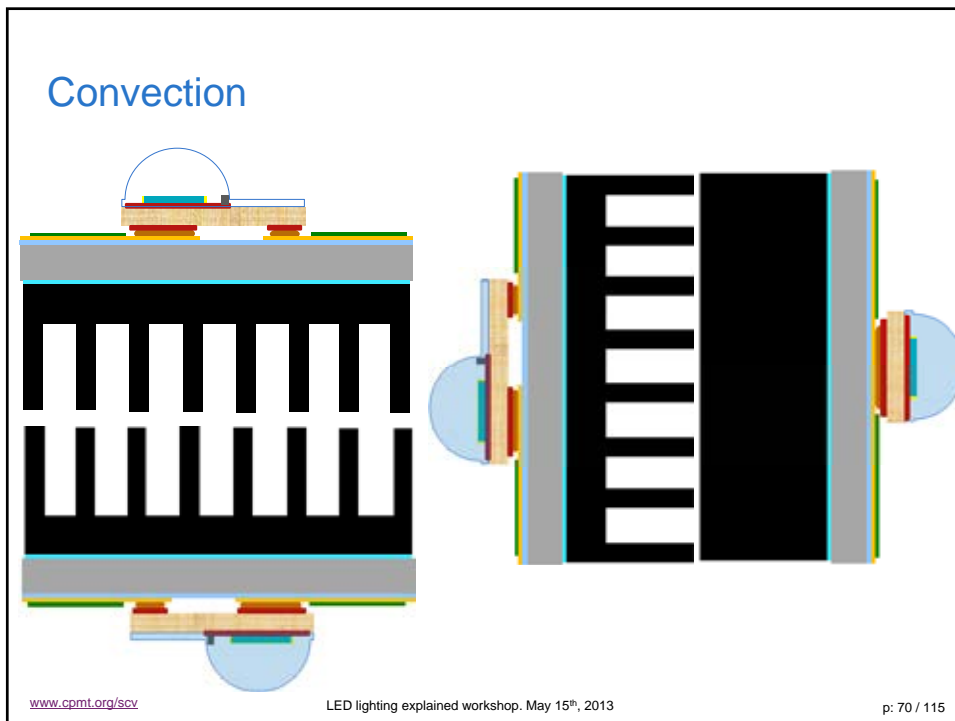
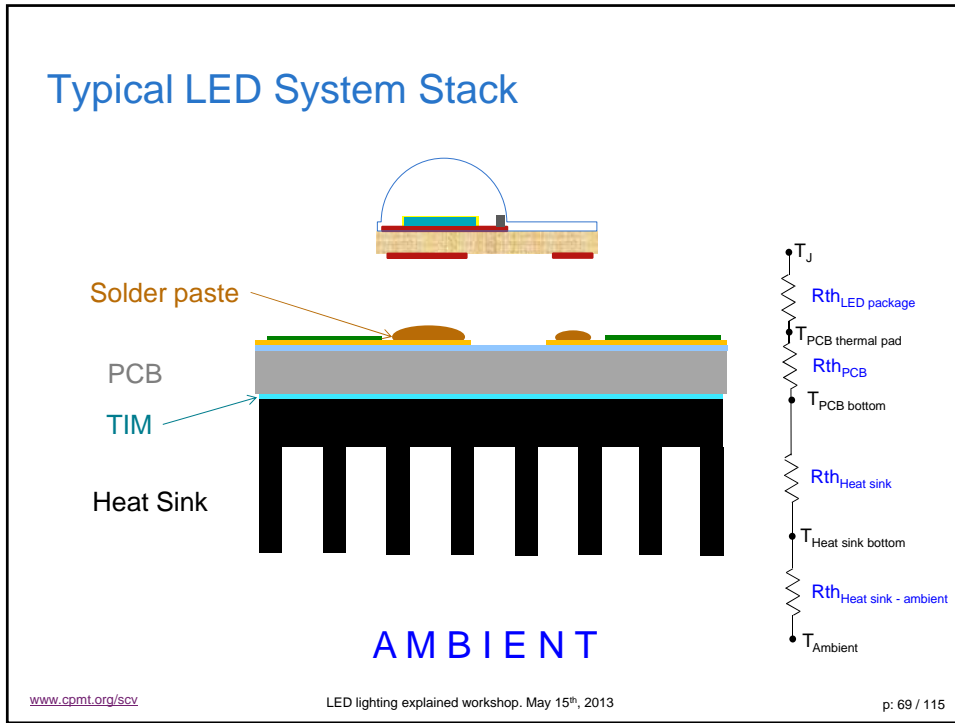
- $R_{th} = (T_1 - T_2) / P_{\text{heat dissipation}}$
- Unit in K/W or °C/W

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

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p: 68 / 115



PCB Construction & Design

Level
2

MCPCB
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Thermal Interface Material (TIM)

No TIM

Max board temp = 52.2C@60 Minutes

After adding TIM

Max board temp = 47.8C@60 Minutes

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Heat Sink

450
400
300
300
200
200
100
100
0

Al: $k=170$

OR

Acrylic: $k=0.18$

40 K/W

0.4 K/W

16

Thermal Conductivity Units are in W/mK .

\$\$\$\$\$\$

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Junction Temperature Measurement

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

Place thermocouple here

Solderability indicator pads

0.8mm or 1.6mm FR4 board with open plated through hole via design mounted on a heatsink

LUXEON LED

Thermocouple

T_s

T_j

$R_{\theta, j-thermalpad}$

$R_{\theta, thermalpad-c}$

LUXEON LED thermal pad

Heatsink

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Presentation Outline

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

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p: 75 / 115

Electrical – Current or Voltage Drivers?

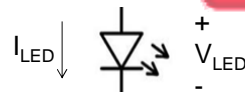
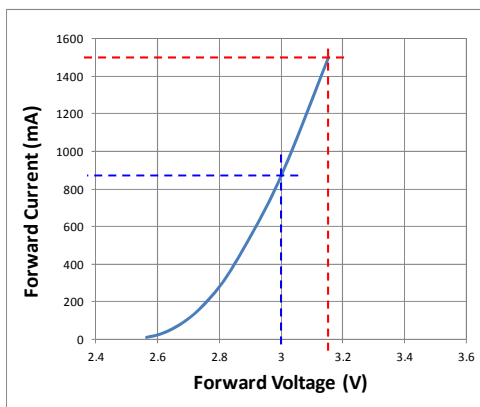
Level

2

Level

3

- Recap



At 3.00V, $I_{LED} = 870\text{mA}$

At 3.15V, $I_{LED} = 1500\text{mA}$

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

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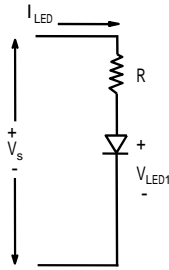
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p: 76 / 115

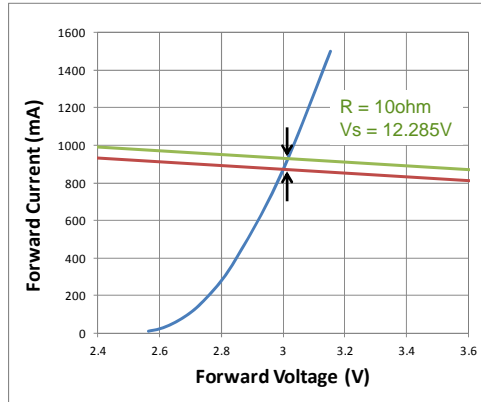
Consideration for Voltage Driver Design

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

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



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

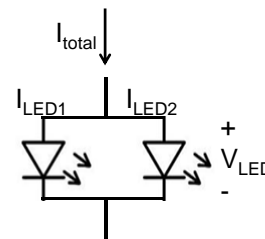
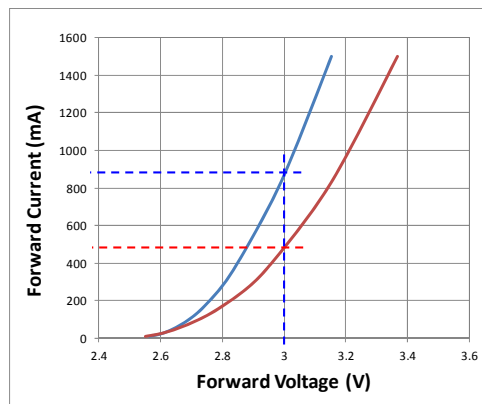


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p: 77 / 115

Electrical – Series or Parallel?

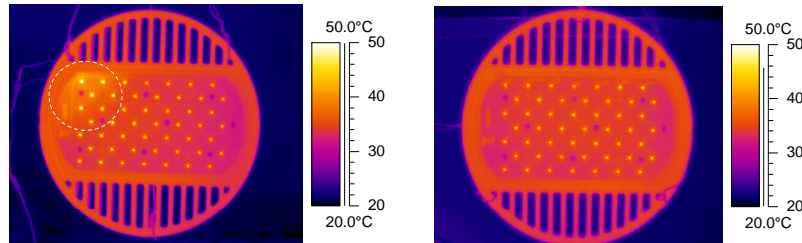


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p: 78 / 115

Electrical Power Distribution – PCB Copper Trace Layout



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p: 79 / 115

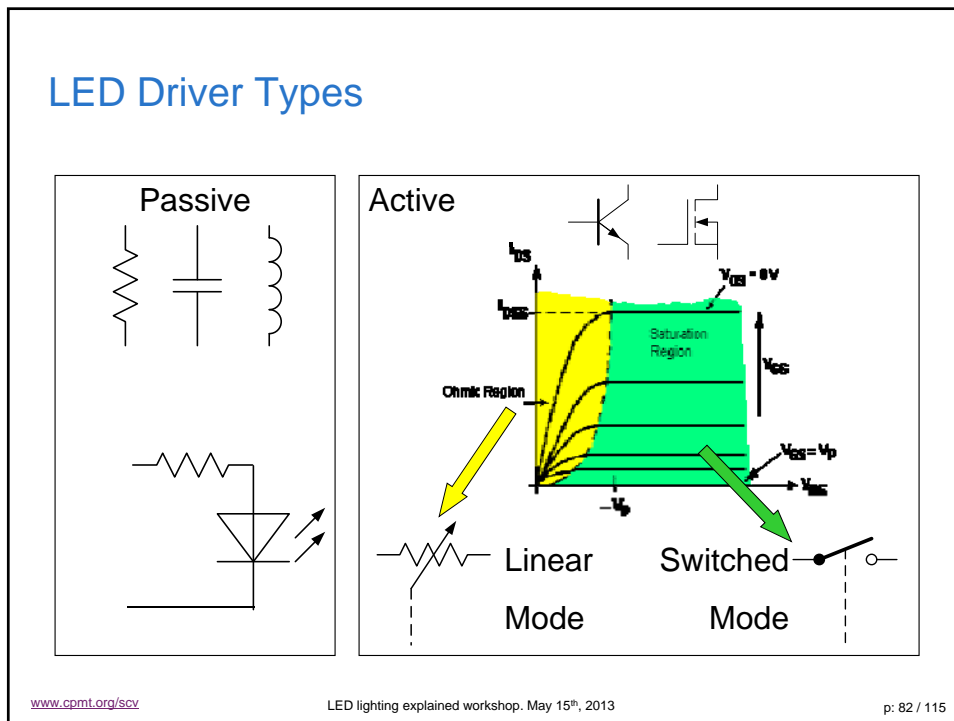
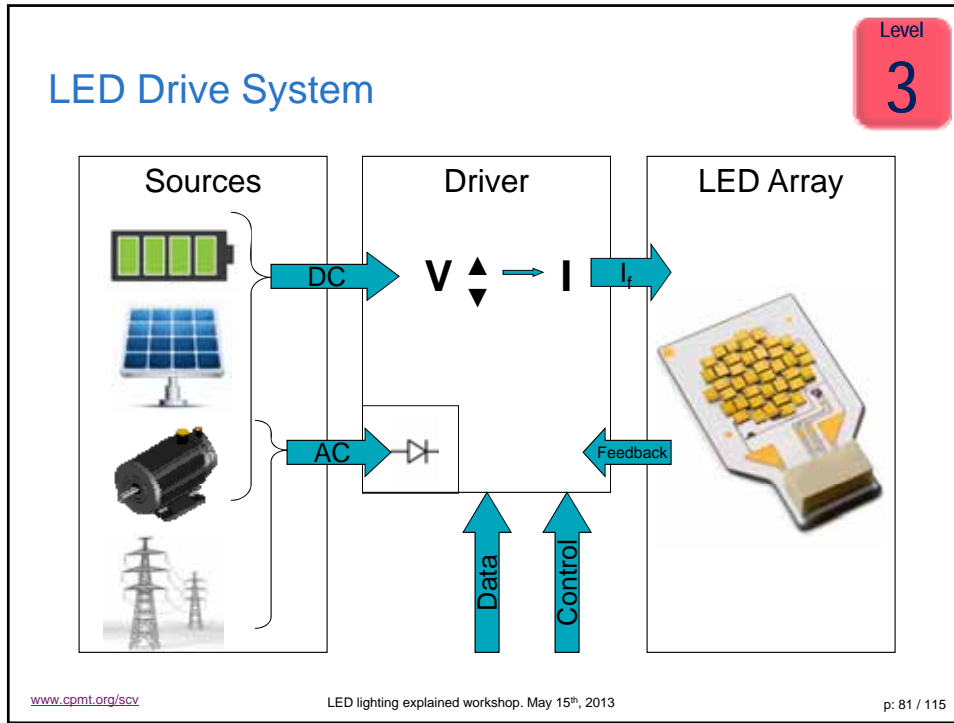
Summary

- 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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p: 80 / 115



Switch vs Linear Analogy

Regulator
Waste

Linear

Switch
Reservoir

Switched

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Linear Regulator (Constant Current Regulator, CCR)

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

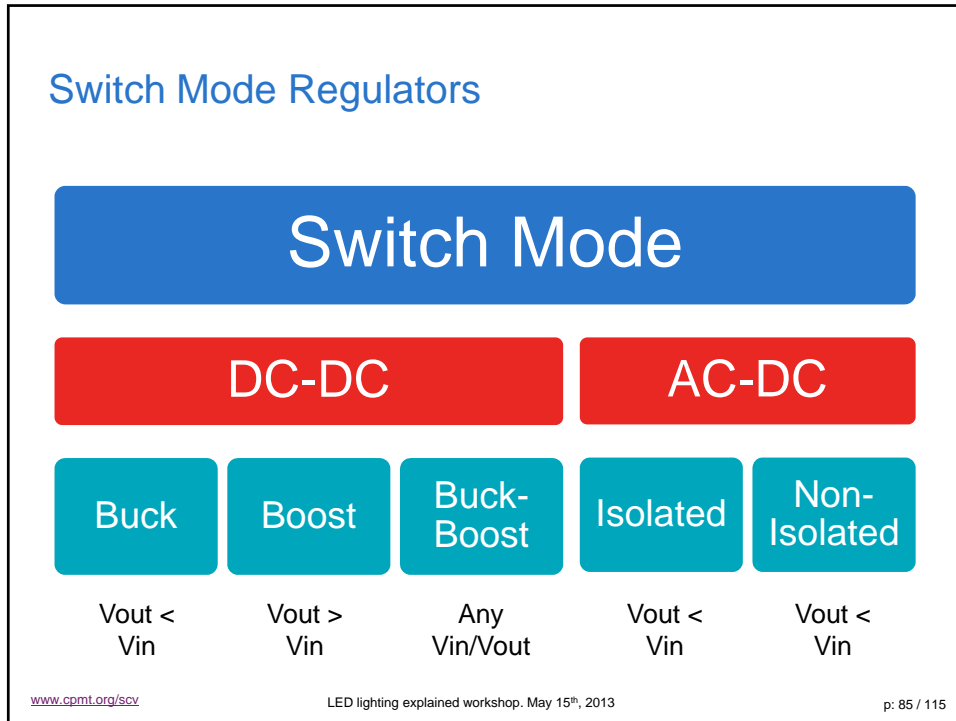
$$P_{in} = V_{in} \cdot I_f$$

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

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

Typical efficiency ~ 70%
 Typical current variation $\pm 5\%$ with $V_{in} \pm 10\%$

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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

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p: 86 / 115

Other Electrical Considerations



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

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

Optics

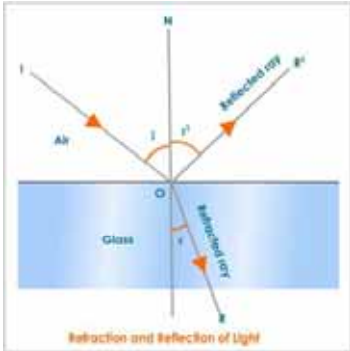
Level
3



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Basic Principles

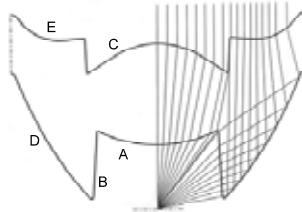
- Refraction (Snell's law)
- Reflection
- Absorption and Transmission



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Optical Design

- 1) Optical software simulation such as ASAP, LightTools, Zemax, TracePro, Photopia
- 2) LED light source
 - Optical model creation using the above optical software
 - Measured rayset

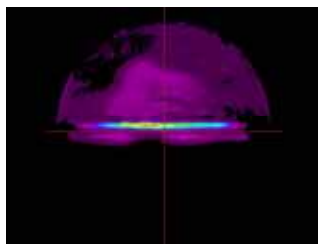


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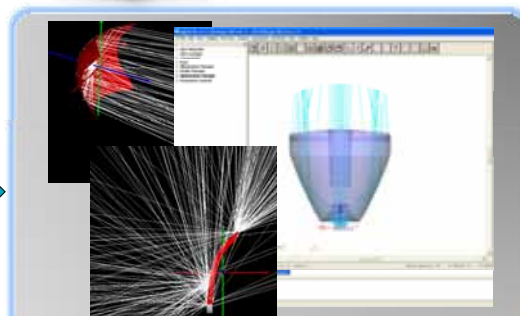
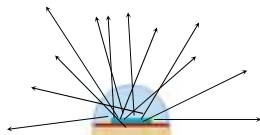
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p: 91 / 115

Rayset



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



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p: 92 / 115

Optics Consideration

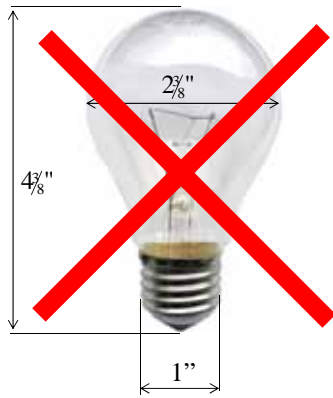
- Optical efficiency ~85%-90%
- LED light source distribution
- LED apparent source size
- Final optics size
- Material selection (polycarbonate, PMMA, glass)
- Fire safety consideration (UL)

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Building a Lamp System or Luminaire – A19 Bulb



Level
3

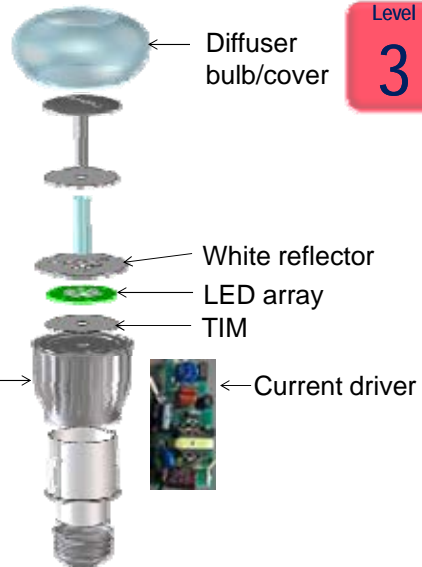
- Cost
- Efficiency

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p: 95 / 115

A19 LED Bulb Assembly



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p: 96 / 115

A19 Sub-Components



Plastic housing, E26 screw & electrical contact pin



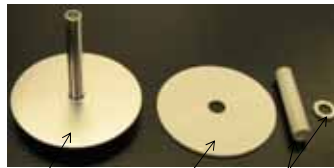
LED driver



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

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p: 97 / 115

Technical Evaluation



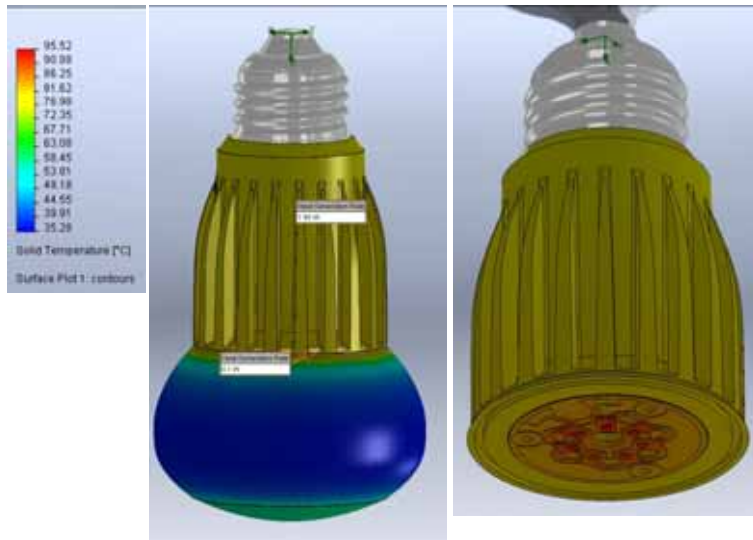
	Energy Star Requirement	60W
LED Count	-	7up LXH8-PW30
CCT	ANSI	3000K
CRI	80 min	80 min
Lumens (min)	800	800
Lm/W	55	58
Beam Angle	+/-135 within 20% of avg	Yes
Lumen Maintenance	>70% (L70) 25Khrs	>70% (L70) 25Khrs
Input Voltage	-	110 VAC
Bulb Power	-	13.7W
Current	-	575 mA
Driver	-	Marvell
Driver efficiency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

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p: 98 / 115

Thermal



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p: 99 / 115

Philips A19 60W L-Prize



- InGaN chip WPE improvement
- Remote phosphor
- Thermal design

Source: 60W Replacement Competition

60W Replacement Competition

Philips Lighting North America won the first L-Prize, and the race to be first across the finish line inspired a global R&D team and a new technology platform. It also drove continuous innovation, accelerating enhancements to successive product designs in the Philips product line.

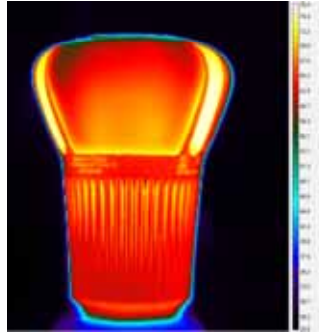


These snapshots of CALPER and LED Lighting Facts[®] listed onedirectional lamps show the significant progress between 2008–2009 and late 2012. Prior to the submission of the 60W replacement lamp L-Prize entry by Philips, no other products listed by DOE were near the L-Prize output and efficacy levels. As of late 2012, a growing number of products can meet the L-Prize levels.

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115

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



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p: 101 / 115

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p: 102 / 115

Street Light



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

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p: 103 / 115

Los Angeles before LED Retrofit project (2008)



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

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p: 104 / 115

Los Angeles after LED Retrofit project (2012)

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



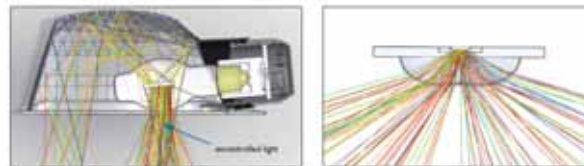
Photo credit: City of Los Angeles, taken from Mount Wilson

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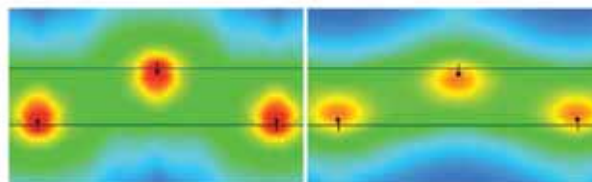
p: 105 / 115

LEDs Enable Superior Light Shaping Capability



HID lamp with reflector

LED with lens

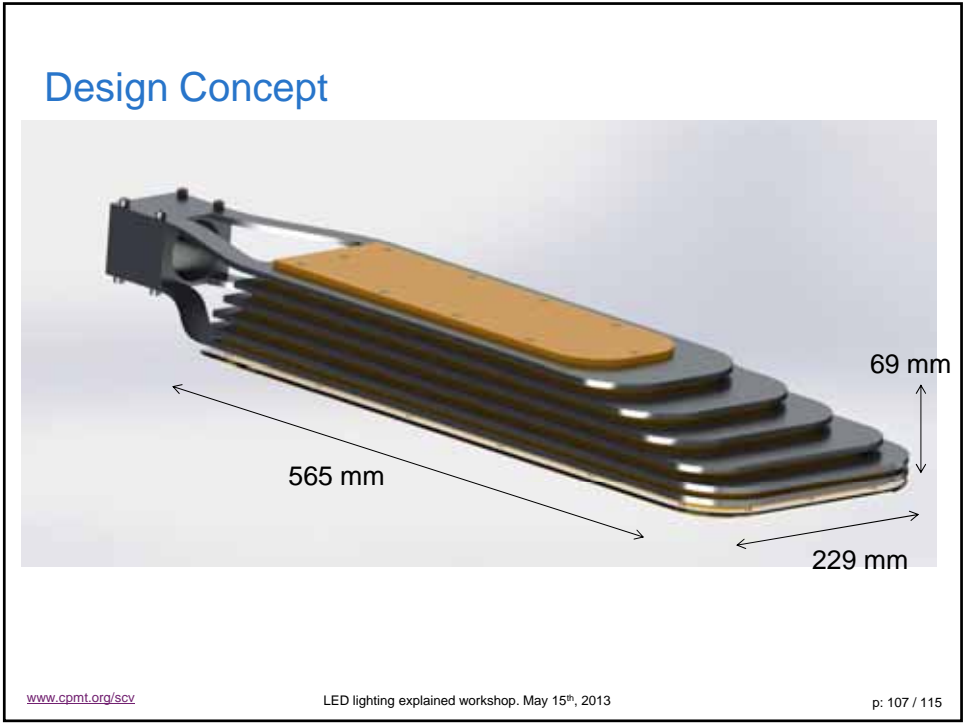


The HPS luminaire (left) concentrates a lot of light below and behind the pole. The LED luminaire provides more uniform lighting on the roadway, while minimizing light trespass.

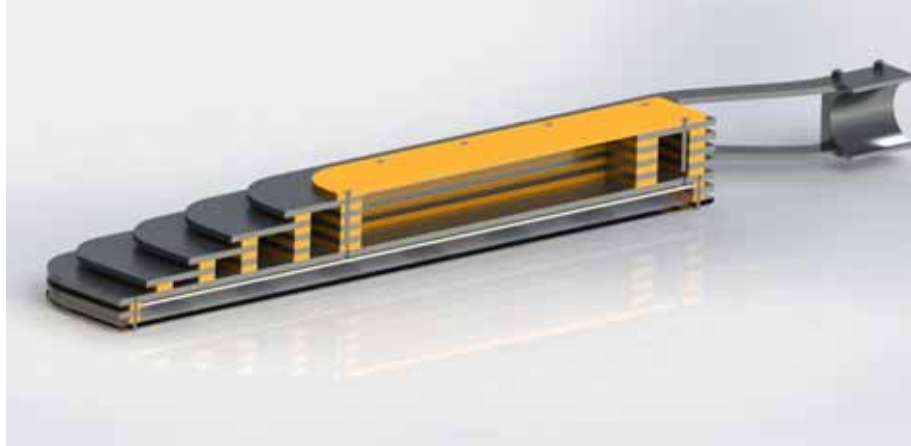
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p: 106 / 115



Cross section



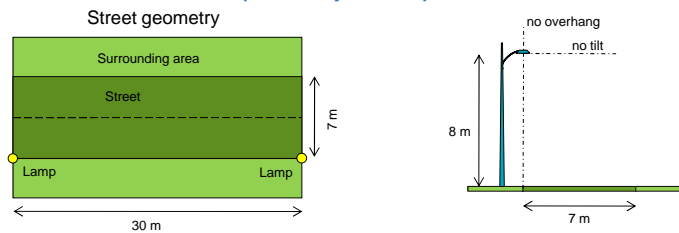
- Room for the Advance 150W outdoor driver
- Hollow sections to save weight

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p: 109 / 115

Street Geometry and Performance Requirements Based on ME3a (European)



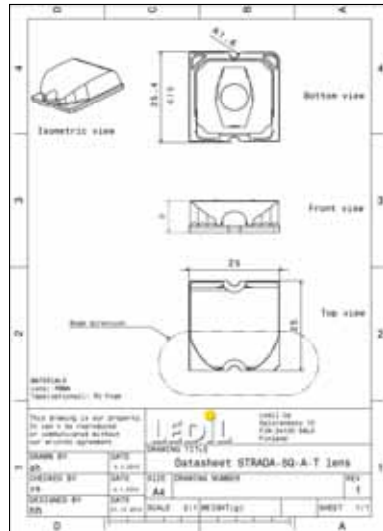
Street geometry:		Lighting class: ME3a	
- Road pavement:	R3 classification	- Average luminance (Lavg):	1 Cd/m ²
- Pole height:	8 meter	- Overall uniformity (U _o):	> 0.4
- Pole distance:	30 meter	- Longitudinal uniformity (U _l):	> 0.6
- Street width:	7 meter	- Threshold increment (TI):	< 15%
- Number 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)		

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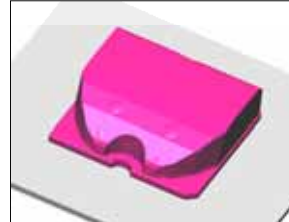
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p: 110 / 115

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 luminaire models	End of February
Strada-SQ-T-DNC	asymmetric	Street lighting IESNA Type II for luminaire models	End of March

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p: 111 / 115

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.

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p: 112 / 115

The End Questions?

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p: 113 / 115



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