IESNA 2004

From Concept to Reality to the Future

IESNA Great Lakes Region

Education Fly-In

Keith Scott

June 2004

LUMILEDS

Presentation Agenda

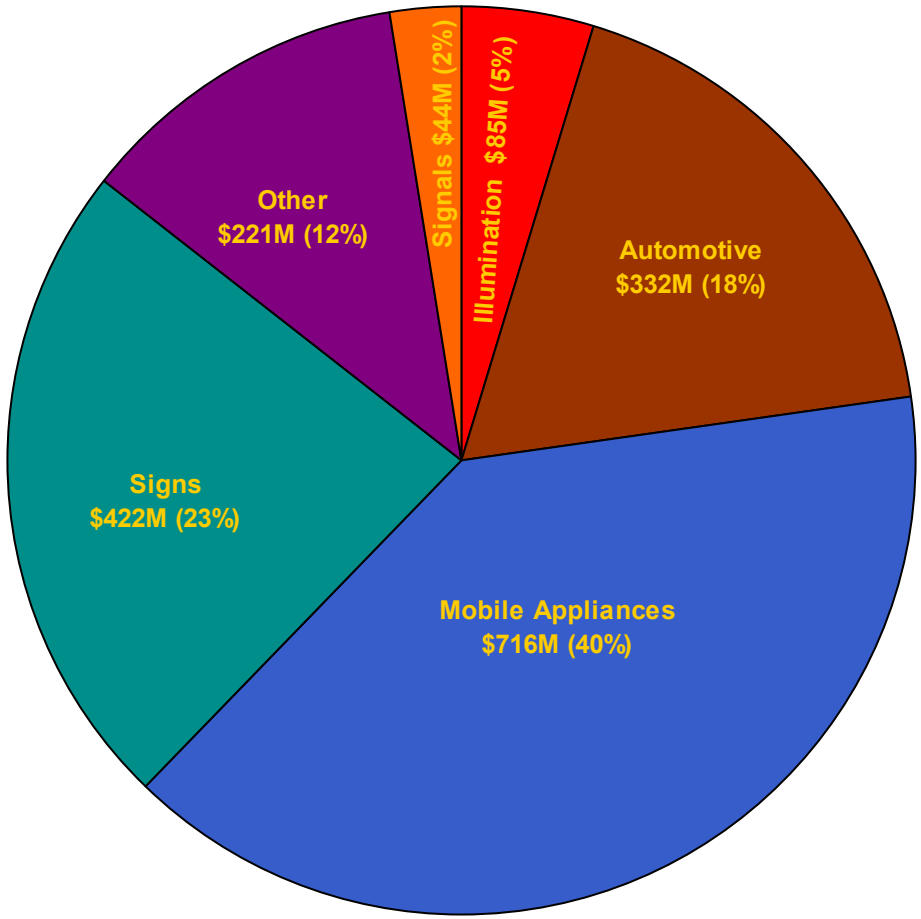
- Introduction
- Solid State White Light
- Technology
- Luminaires and Applications
- Integration

Why LEDs? - Key Technology Advantages

- **High efficacy (Presently 25-30 Lumens/Watt)**
  - Red 10x Better that (filtered) incandescent
  - White 2x better than incandescent
  - Potential efficiency 150+ Lumens/Watt (2x better than fluorescent)
- **Much greater design freedom**
  - Dynamic Color Flexibility including many “whites” without filters
  - Size and shape flexibility for styling and fixture design
  - Instant on and fully dimmable with no color change
  - No heat or UV in beam
- **High Reliability**
  - Rugged Solid State construction
  - Long lifetimes (5,000-100,000 hours); low maintenance
  - No catastrophic failures
- **Environmentally friendly**
  - Minimal disposal required
  - No mercury
  - Potential savings of $17B in annual energy costs (30 large power plants)
  - Potential reduction on CO_2 emissions of 155 million tons

Applications of High Brightness LEDs in 2002

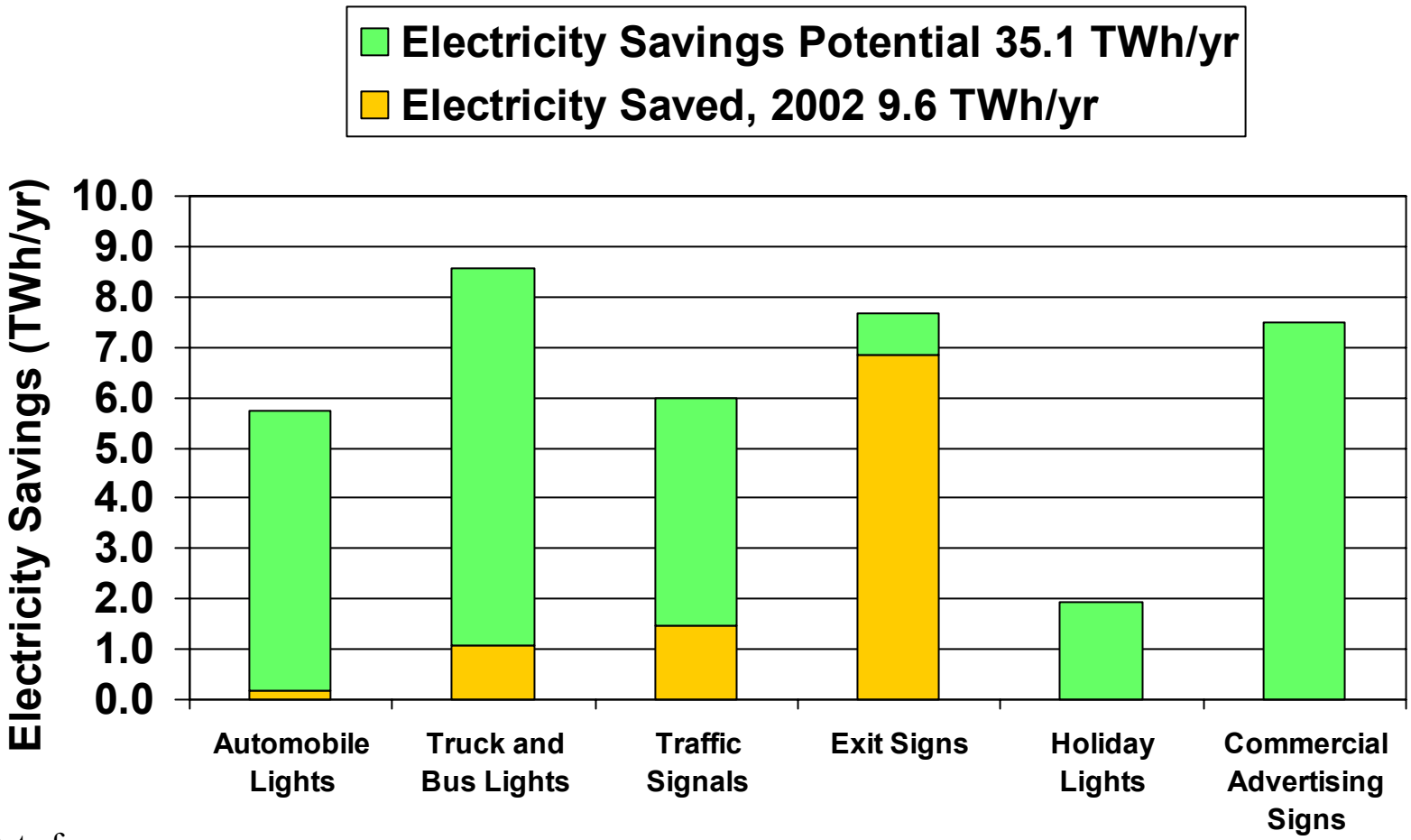
Total $1.82 Billion



Illumination Segment expected to grow to $522M (12%) in 2007

Adapted from: "HB-LEDs the Market Drive towards Solid-State-Lighting" by Bob Steele (Strategies Unlimited) Published in "Compound Semiconductor December 2003

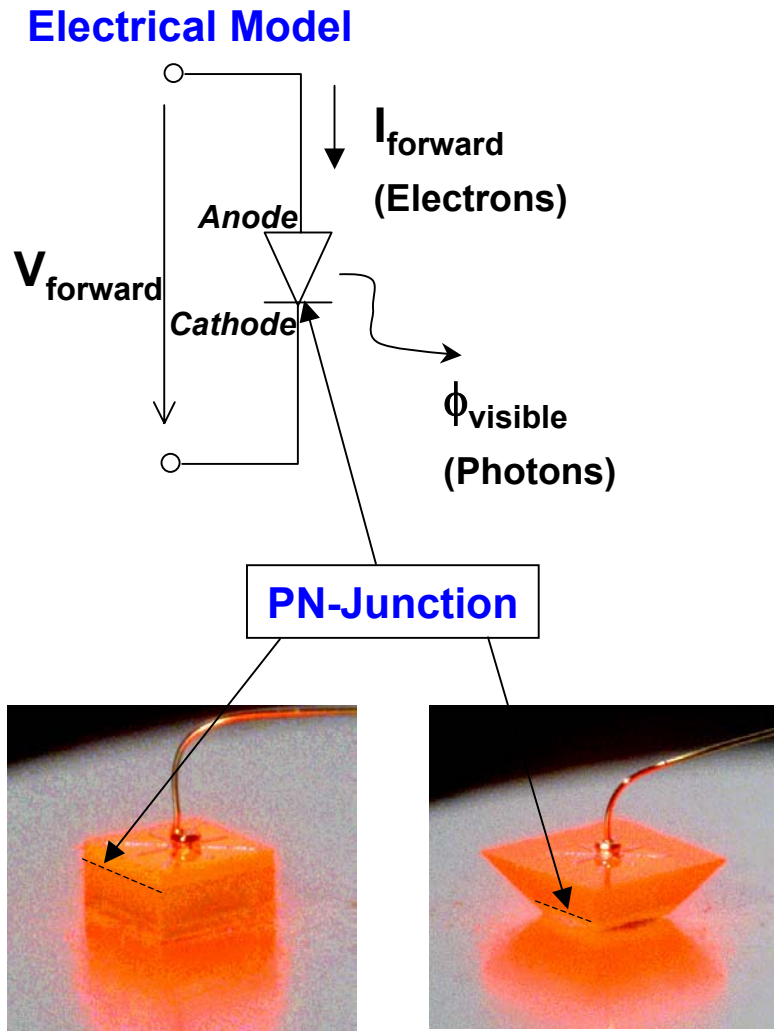
Electricity Saved and Potential Savings of Selected Niche Applications



Data from :
"*Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications*"
U.S. Department of Energy
November 2003

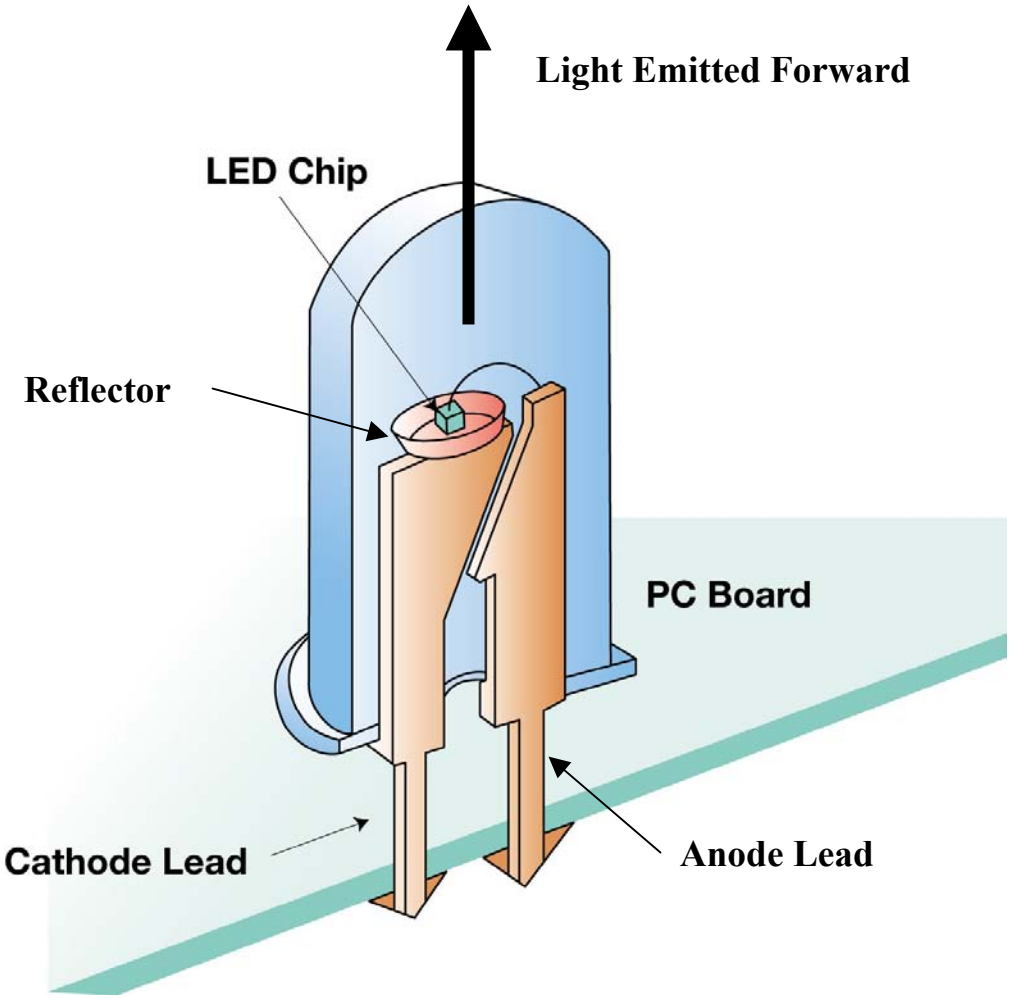
Language

- *Die* = chip: heart of the LED
- *LED* - chip in a package
- *PN Junction* - where the light is created in the chip
- *AlInGaP & AlGaS*: red - yellow technology
- *InGaN* - green – blue +white technology
- *Level 1* – the chip or die
- *Level 2* – the LED
- *Level 3* – a LED array; may include optics, heat sink and/or power supply
- *Level 4* – LED luminaire
- *Driver* = ballast
- *Thermal Resistance (C/W)* - a measure of the heat transfer capacity of the LED - lower is better
- *Binning* - subdivision of the manufactured "distribution" into common operating parts (color, flux, forward voltage)



What is a LED?

Low Flux LED



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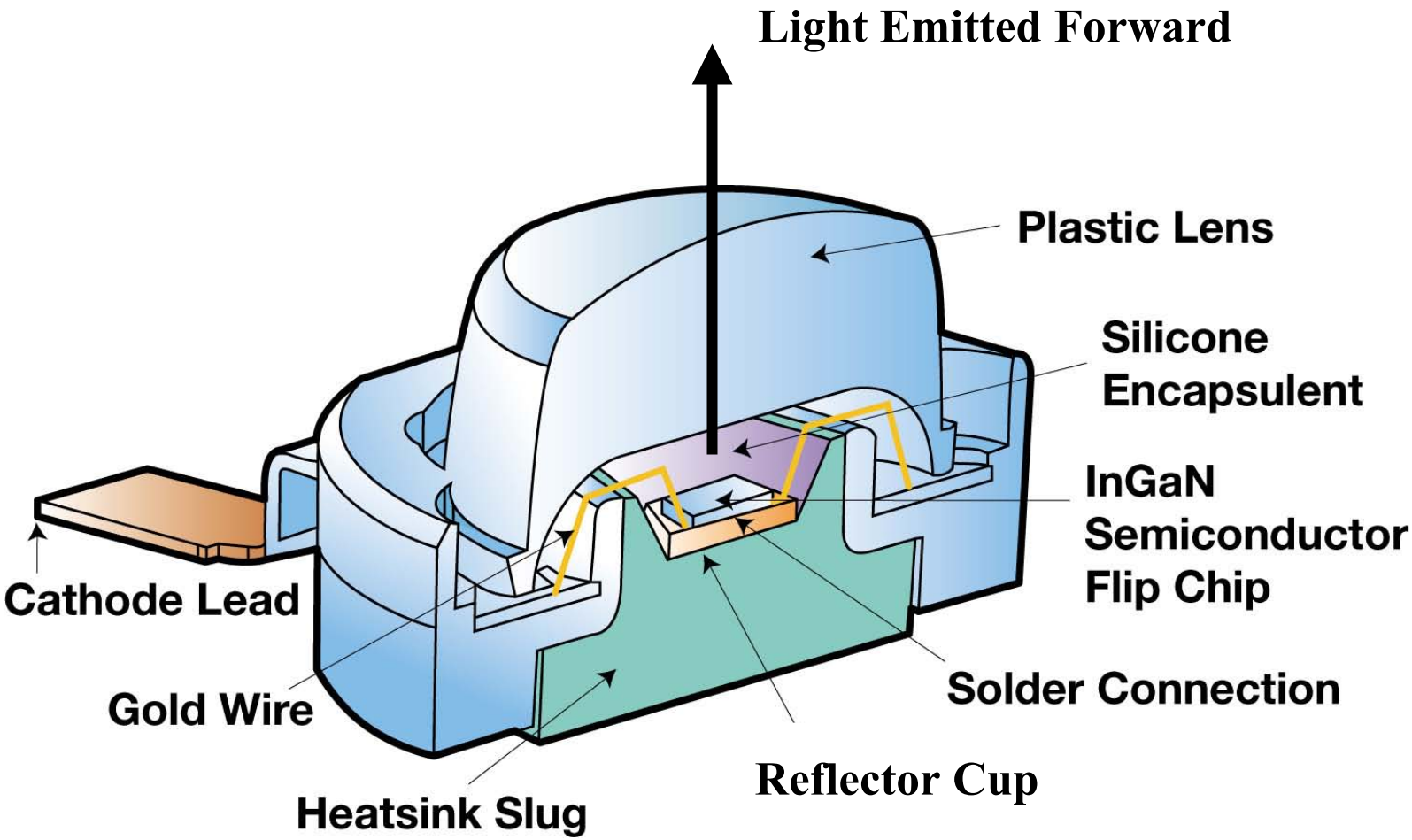
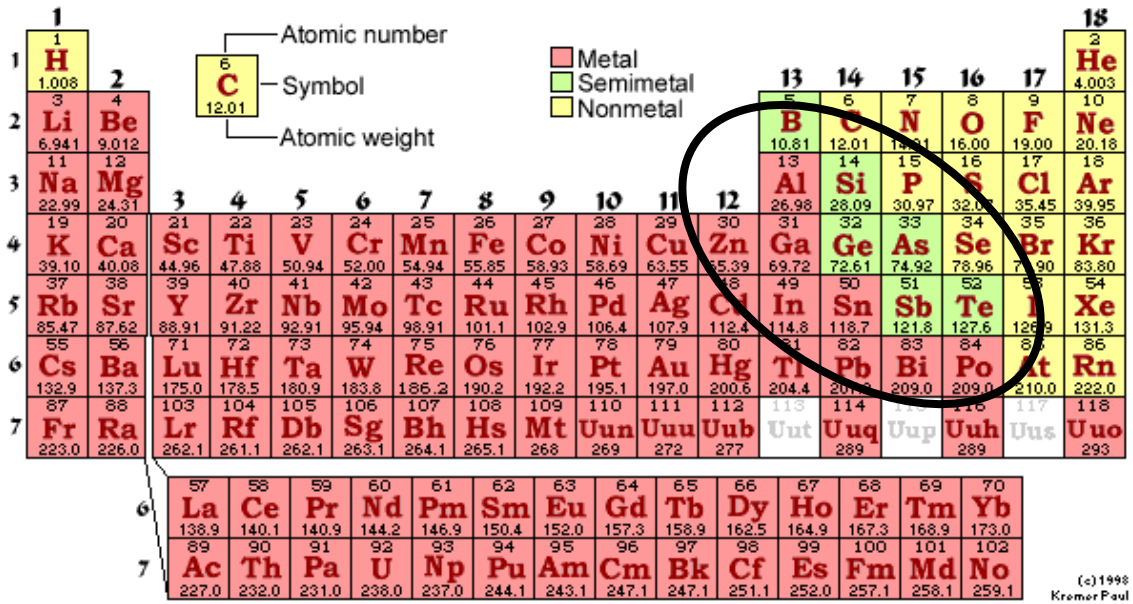
What is a LED?



What is a LED?

LED's Defined

- The exchange of positive and negative charges between these materials results in the emission of photons.



The Periodic Table

Courtesy io Lighting

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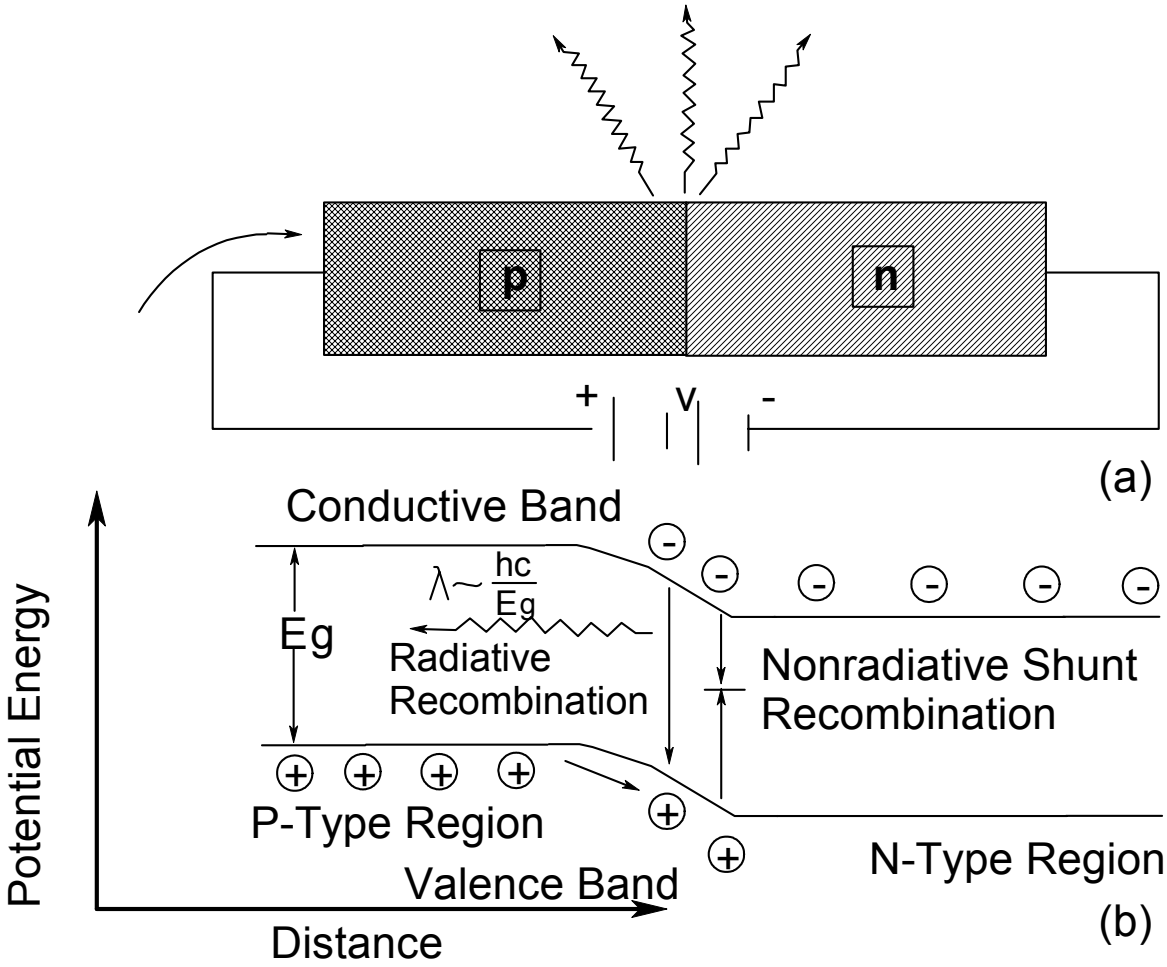
What is a LED – How does it work?



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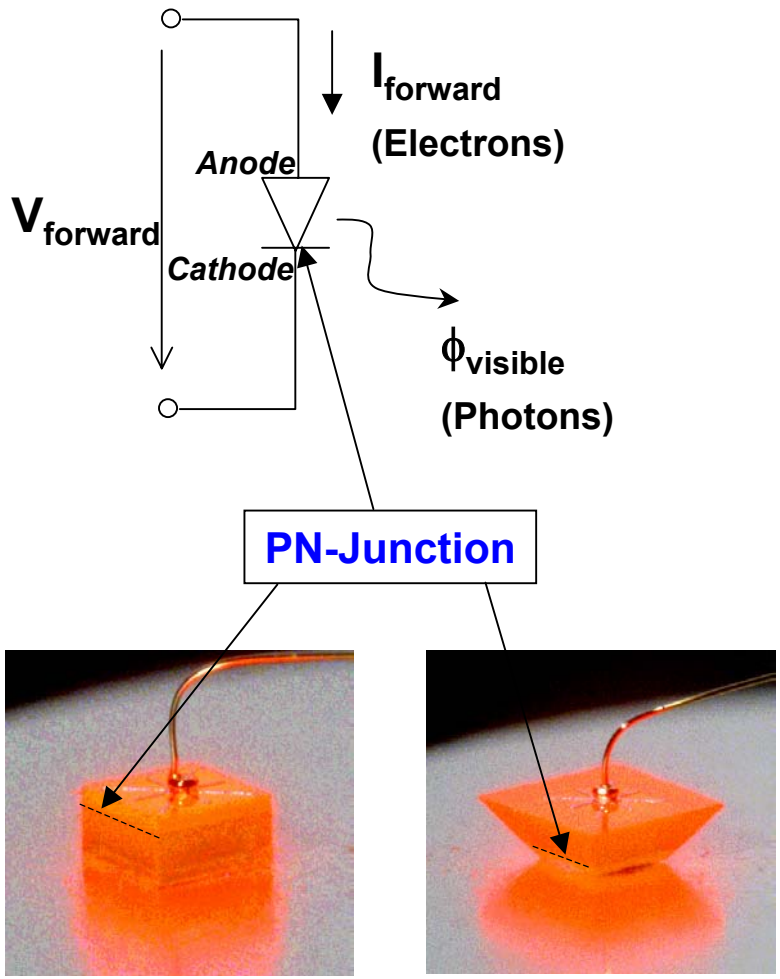
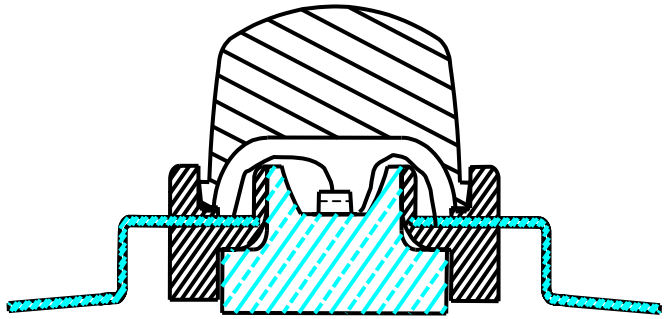
Working Principle of an LED

Electrical Model

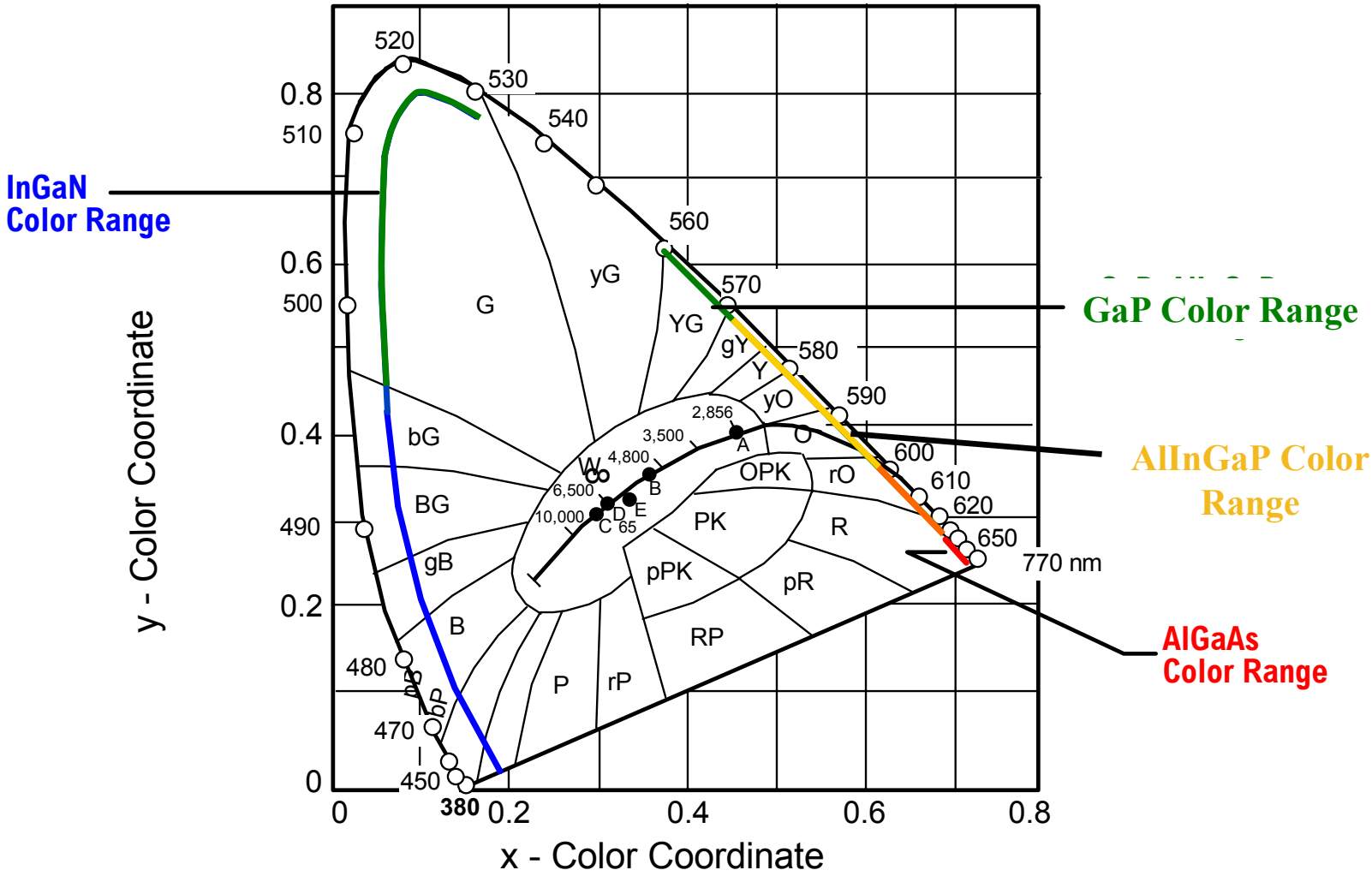




- Same principle for all colors (AlInGaP & InGaN)
- Power dissipation:1-5 Watt
- Package Extraction Efficiency: >95%

- Maximum Ratings
  - $T_{junction-max}$ = 120°C
  - $I_{forward-max}$ = Product dependent

LED Color Ranges



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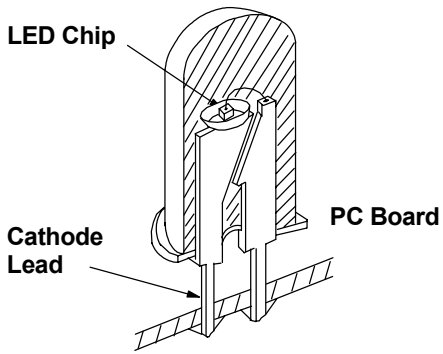
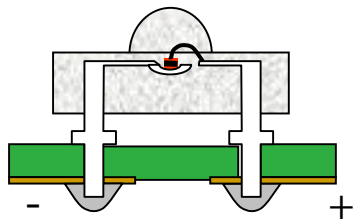
Historical Development of LEDs

- 1962 – first LED, a novelty in the lab
- Late 60s – low output red LEDs (< 1 mcd) find commercial applications as indicator lamps
- mid 70s – Green LEDs
- Early 90s – Blue (Nakamura), completing spectrum
- Late 90s + - commercialization of high brightness LEDs

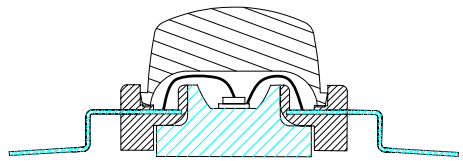
Historical Development - Design Evolution of LED Packages



5mm Lamp
Circa 1970
2-3 lumens
If = 30 mA



SuperFlux
Circa 1992
4-8 lumens
If = 70 mA



Luxeon
Circa 1997
20-40 lumens
If = 350 mA

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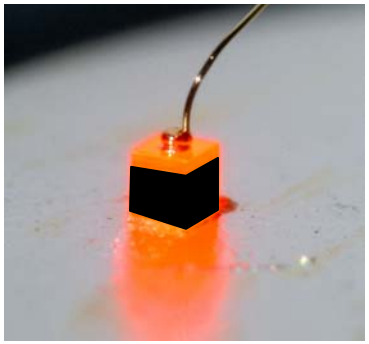
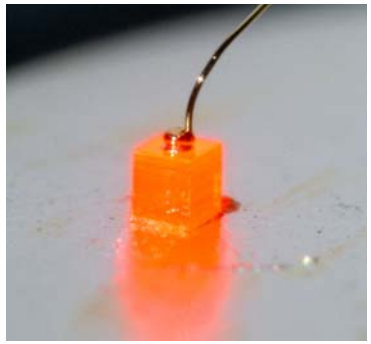
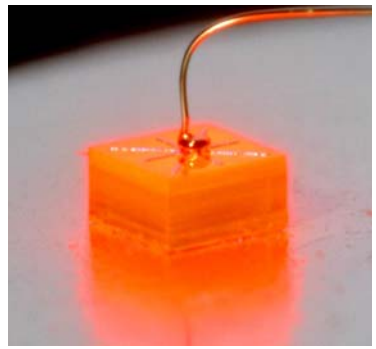
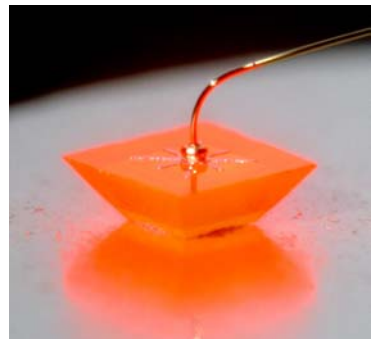
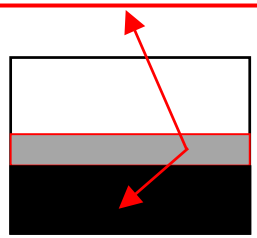
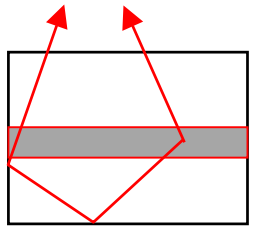
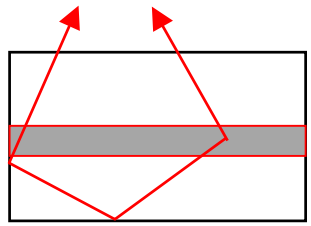
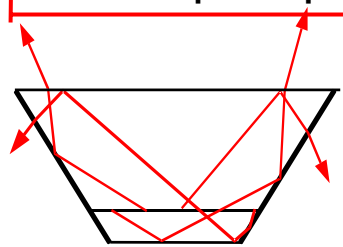
Historical Development - Better Light Extraction

Absorbing Substrate (1991)	Transparent Substrate (1994)	Batwing (1998)	Lambertian (mid 2001)
			
	Increase surface area		Re-shape Chip
			
	~ 3x flux improvement	~ 15x flux improvement	~ 30x flux improvement

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- **Solid State White Light**
- Technology
- Luminaires and Applications
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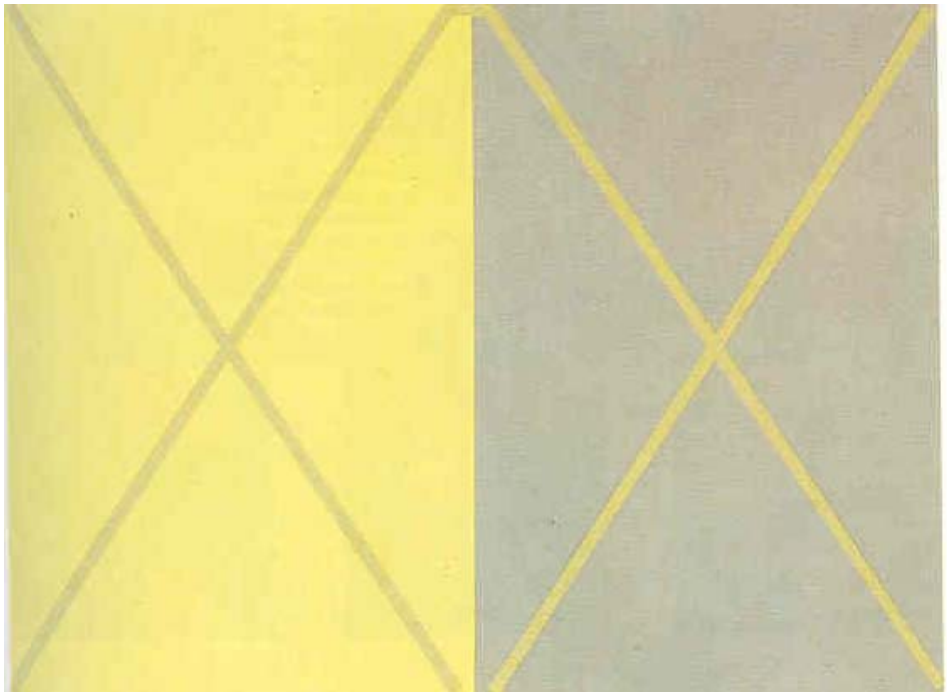
What is the Color Temperature?

Color Edges and Juxtaposition of Colors



The human eye is very good at picking up “edges”. In this example color edges are picked up by the eye, but color perception is muddled.

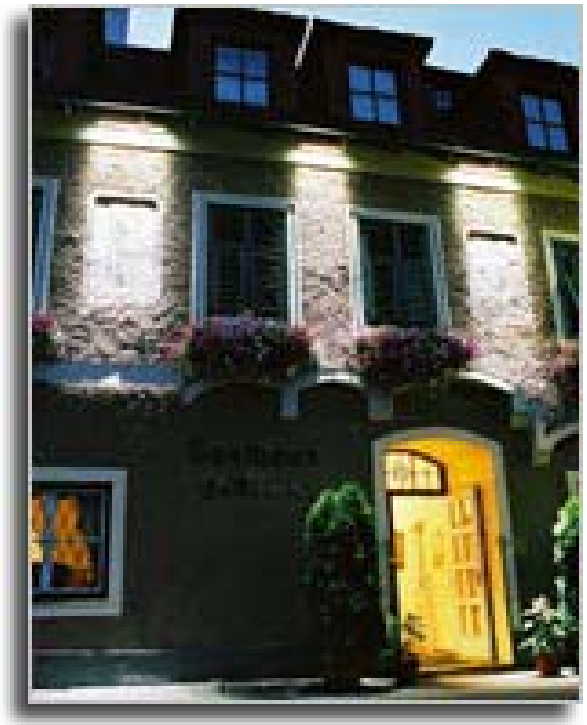
Both “X” shapes have the same spectral power distribution but their appearance differs.

This illustration demonstrates that photo-pigment response in a small region does not determine color appearance in that region.

Color appearance depends on the spatial structure of the image as a whole.

White LED Light

- **Phosphor Coated**
  - What it is…
  - What's Next
  - Features and Benefits
- **Two Approaches**
  - Blue LED + yellow phosphor, (+red)
  - UV LED + RGB phosphors

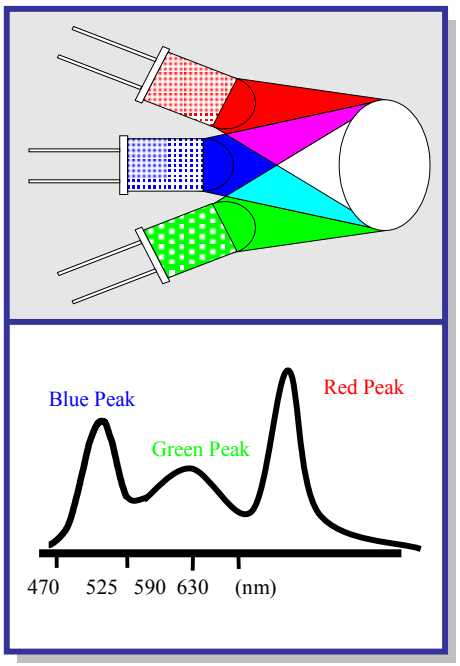


White Light from LEDs

Three methods of Generating LED White Light

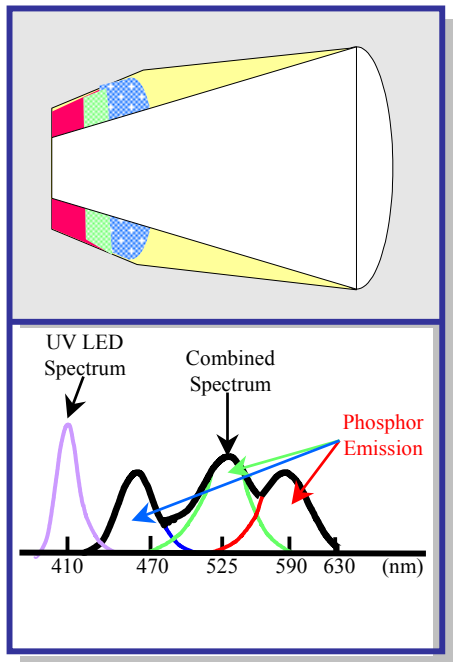
Each method has potential strengths!

Red + Green + Blue LEDs



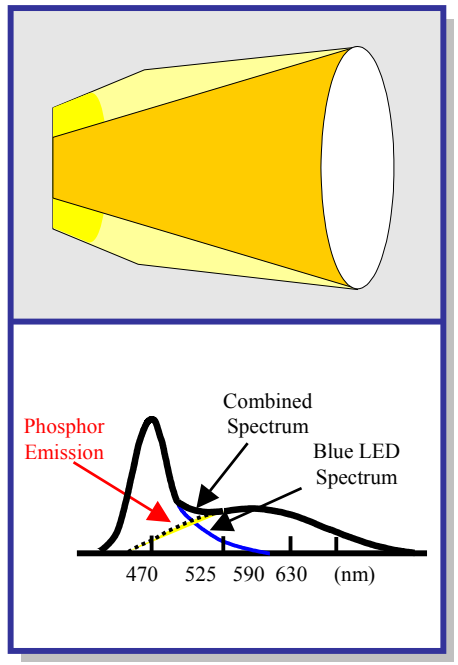
RGB LEDs

UV LED + RGB Phosphor



UV LED + RGB phosphor

Binary Complimentary



Blue LED + Yellow phosphor

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White LED Light

RGB White

- **Advantages**
  - Color can be changed dynamically
  - As a luminance source, millions of colors can be produced
  - Higher efficacy
- **Disadvantages**
  - Requires more complex driver electronics
  - Color shifts due to temperature and aging
  - As an illumination source, color rendition can be tricky

UV LED + RGB Phosphor

Advantages

- Potential for limited "tint" variation
- Simple ballast (driver)
- Good color rendering

Disadvantages

- Lower efficacy
- New phosphor development required
- Potential UV packaging problems, shorter life

Blue LED + Yellow (+Red) Phosphor

Advantages

–Higher efficacy

–Technology exists today

–Cool White: 5500K, 70 CRI

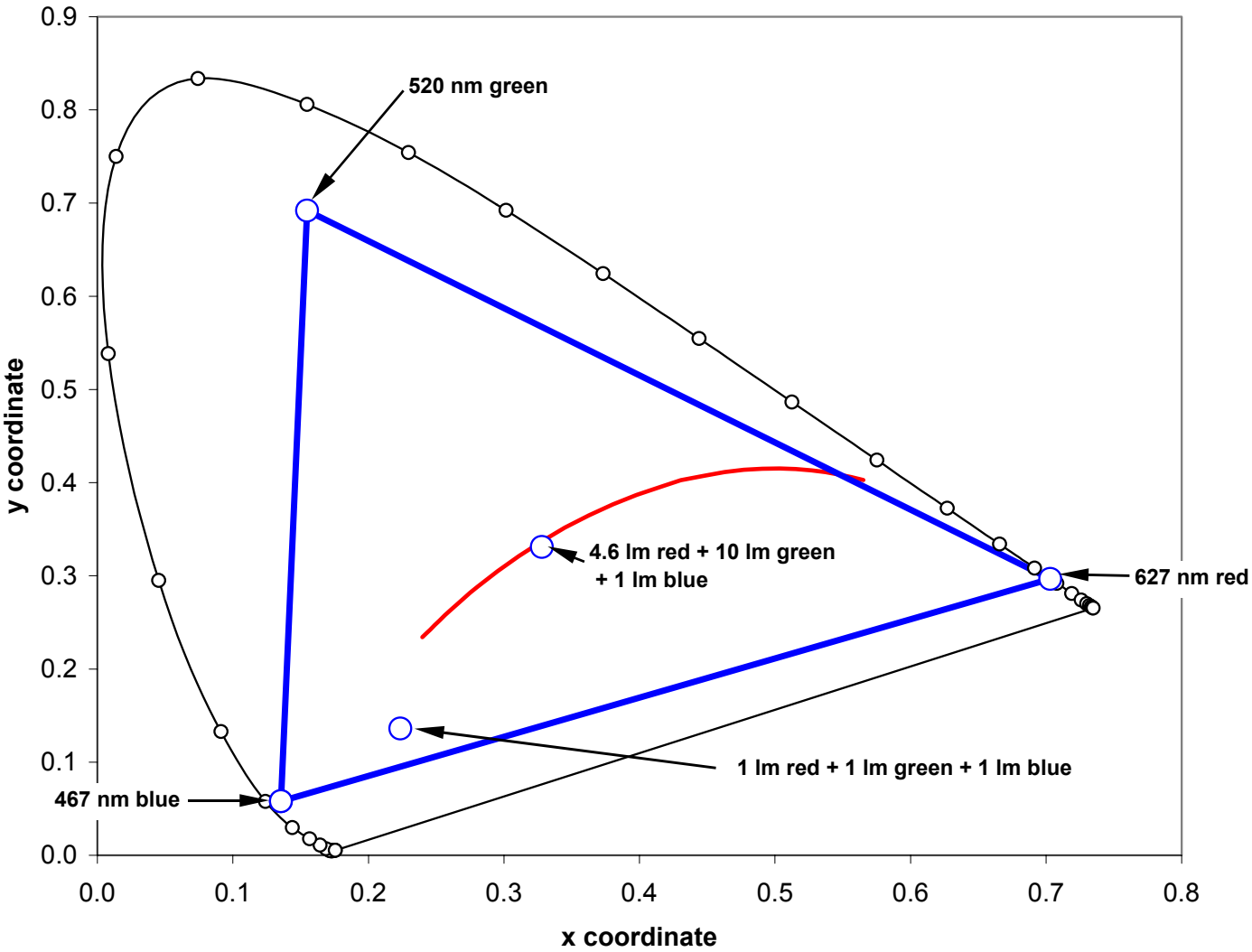
–Warm White: 3200K, 90 CRI

Disadvantages

–Potential for "tint" variation:

Controlled optically and by selection

Mixing of three colors - RGB



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Vivid Colors
from Saturated Red, Green and Blue LED Light source

CCFL

LUXEON

(simulated)

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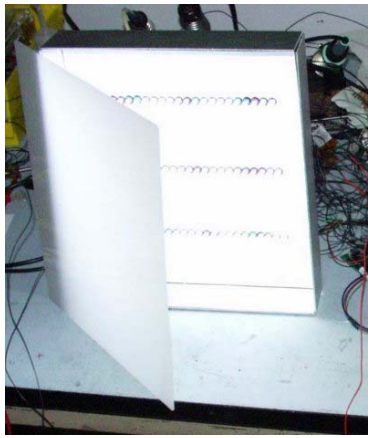
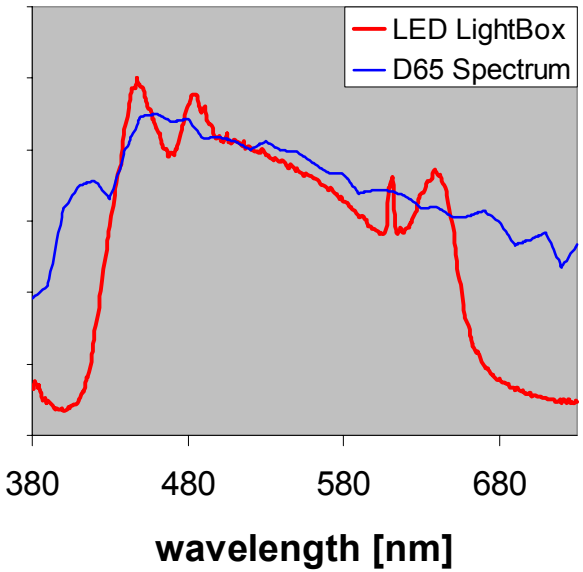
LED Lighting Concept Demonstrations





Index	D65 Light Box
R_1	95
R_2	97
R_3	97
R_4	93
R_5	96
R_6	98
R_7	95
R_8	94
R_9	85
R_{10}	95
R_{11}	94
R_{12}	90
R_{13}	95
R_{14}	98

- **Objective: Duplicate CIE D65 illuminance spectrum between 420-650nm**
- **Mixed RGB + amber + white**
  - 547 lm, 49W (11.2 lm/W)
  - CCT: 6705 K
  - Ra=96
- Excellent color rendering for all indices
- Uniformity across box: $\Delta u'v' < .005$

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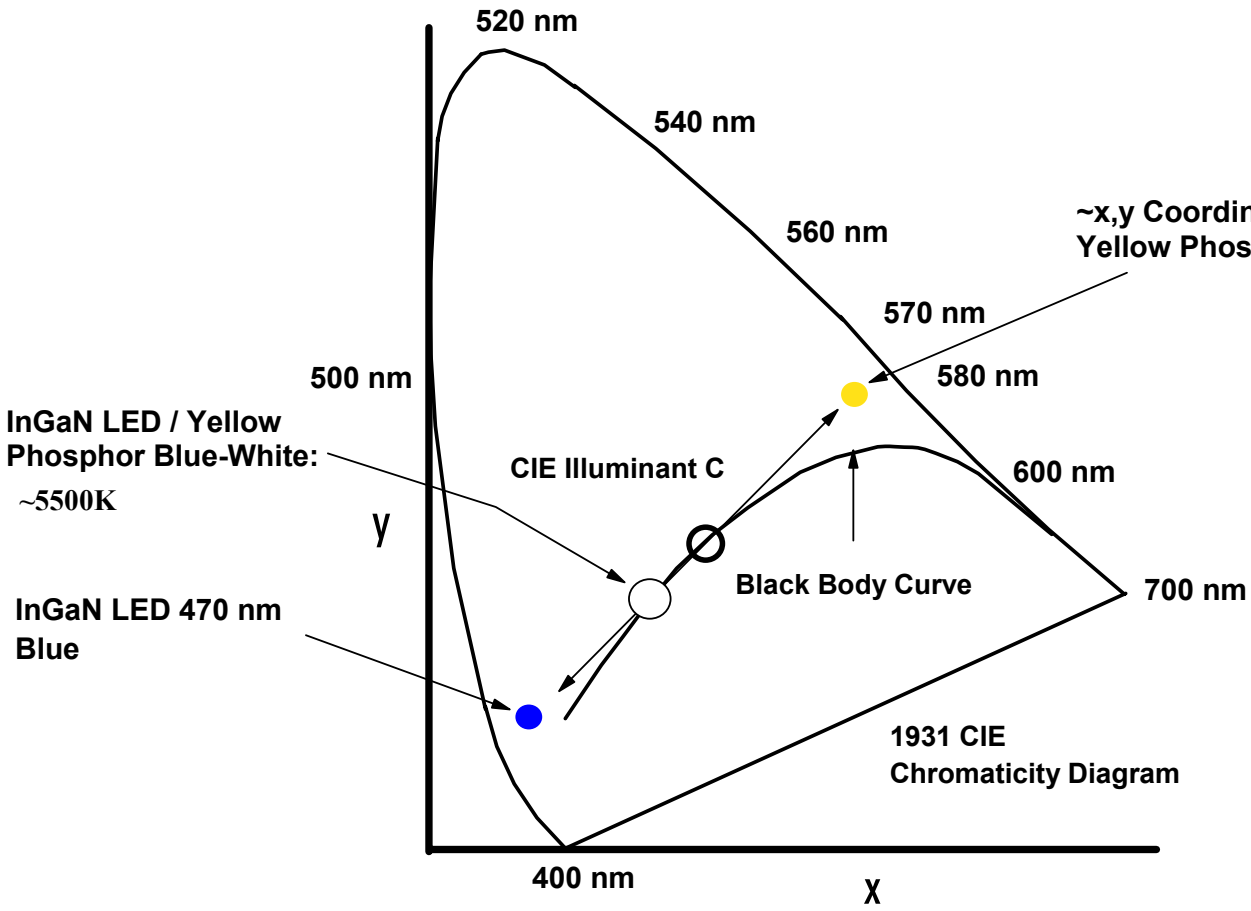
Cool White Phosphor LED Color Coordinates



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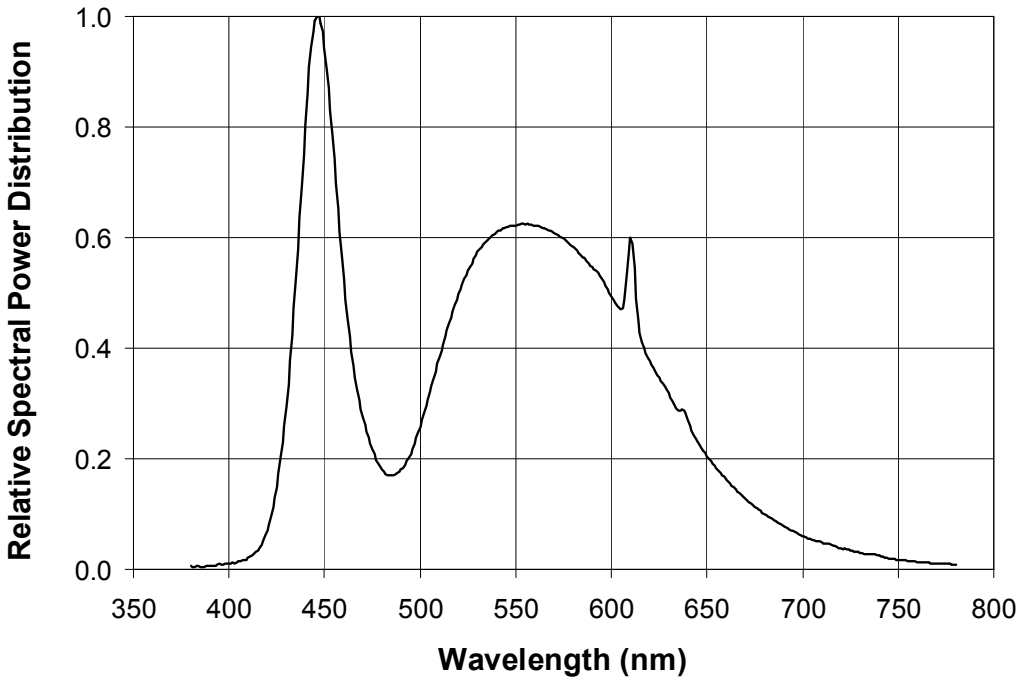
High CCT White Phosphor LED Spectrum



White Wavelength Characteristics:

Typical Color Temperature: 5500K

Current Color Rendering Index: CRI 75

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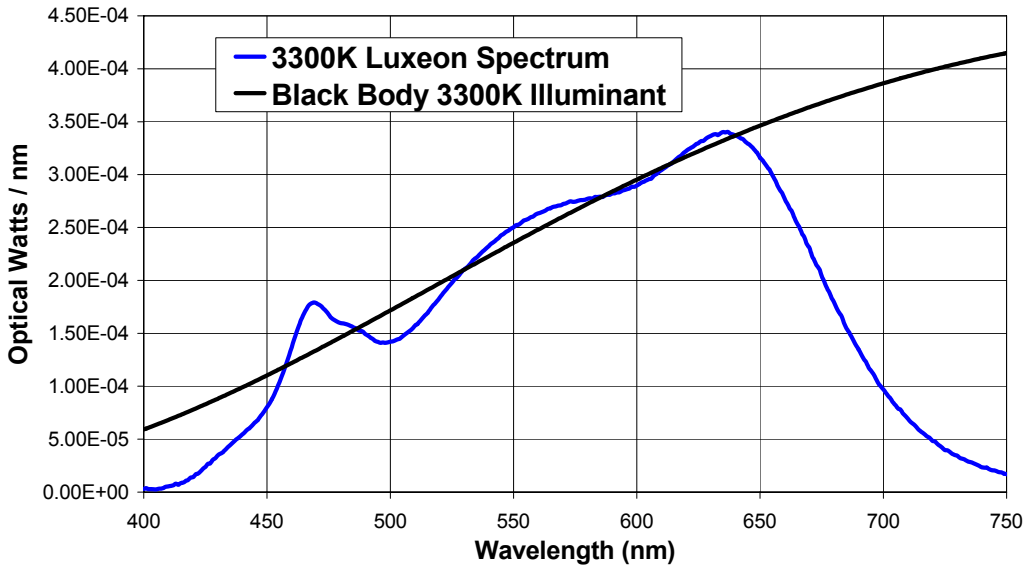
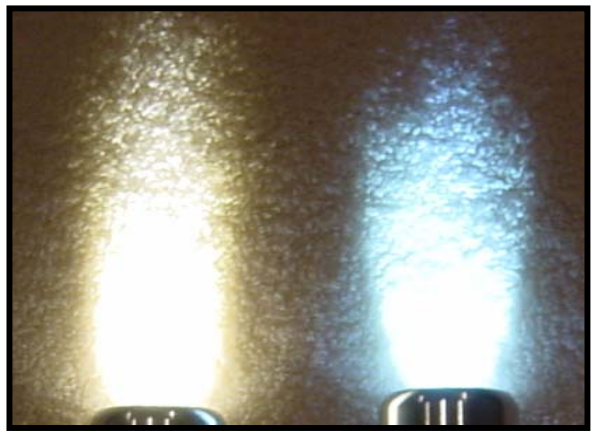
Low CCT / High CRI White Spectrum

- 3200 - 3500K nominal CCT
- Typical CRI > 90





3200K 8000K

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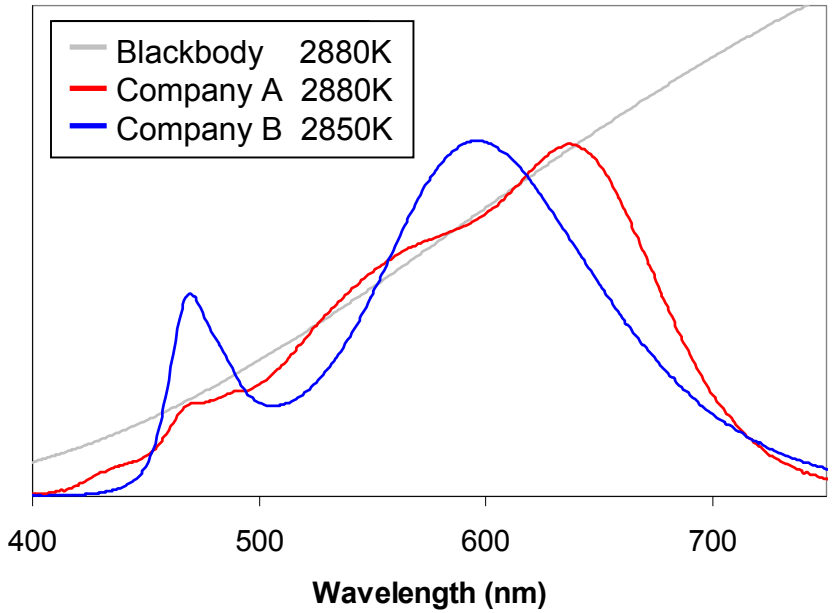
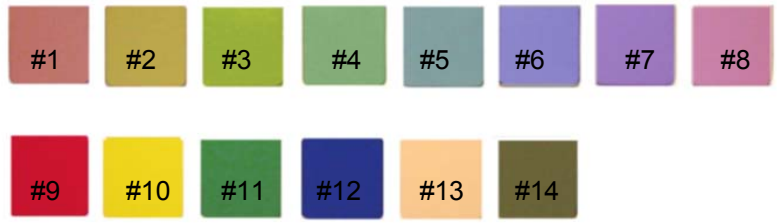
What is the CRI?
Not All Warm White LEDs are the Same



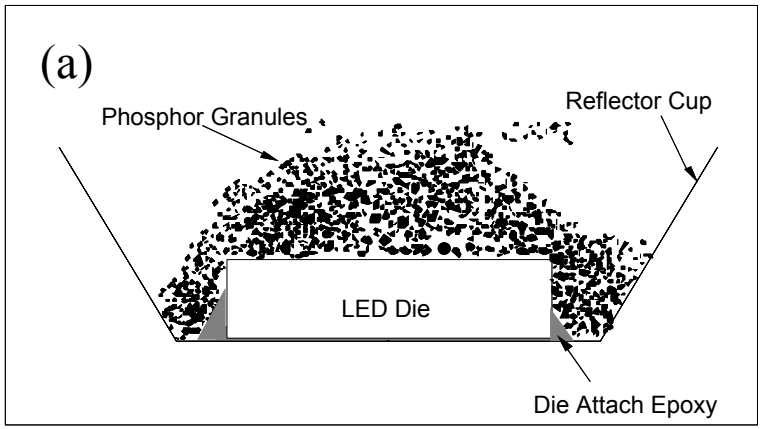


- **Measurements of Warm White LEDs**
  - Limited sampling

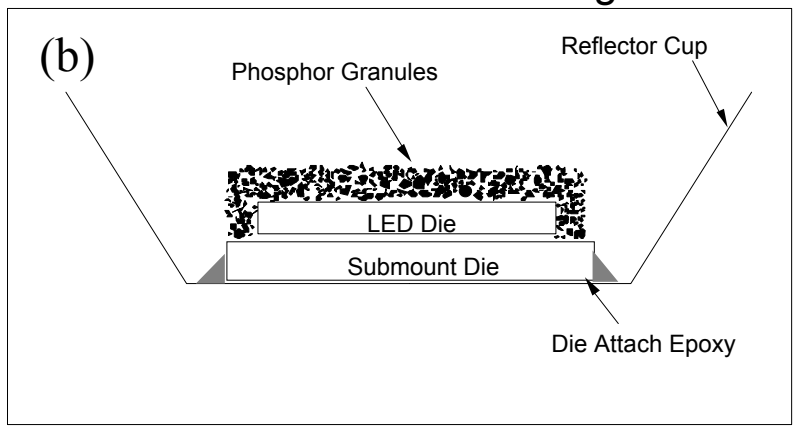
	Company A	Company B	
Ra	**92**	**75**	←
R1	92.1	73.7	
R2	93.5	93.0	
R3	93.6	85.8	
R4	89.9	63.0	
R5	90.1	73.5	
R6	91.4	91.2	
R7	94.6	72.9	
R8	89.8	47.4	
R9	**73.4**	**-8.3**	←
R10	82.6	83.1	
R11	88.2	55.7	
R12	77.7	71.6	
R13	91.8	78.2	
R14	95.9	92.2	

“Color” Variation Among White LEDs

Conventional



New Conformal Coating



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Phosphor Deposition on a Chip

Old Process:

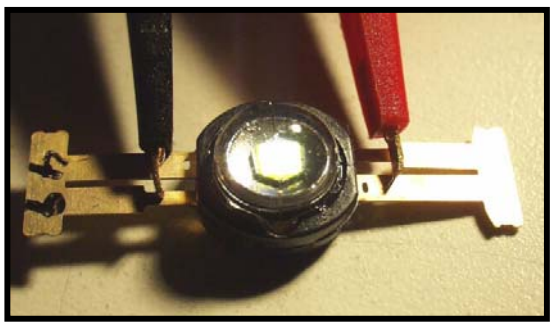
- Blue Light travels different distances through different phosphor thicknesses
- That causes varying CCT at off axis viewing angles

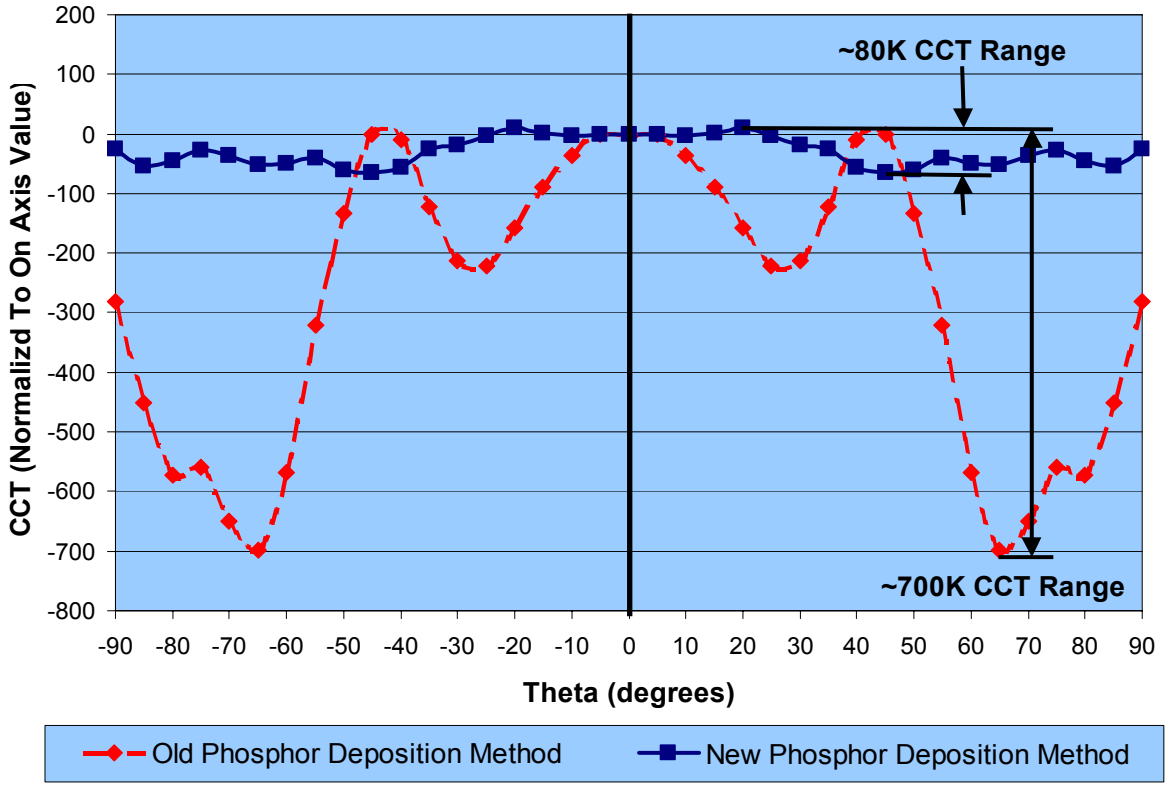
New Process:

- Blue Light travels equal distances through equal phosphor thicknesses
- That generates uniform CCT at off axis viewing angles

Improved CCT Angular Uniformity

- Reduced spread in CCT
- Reduced source size





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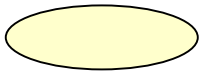
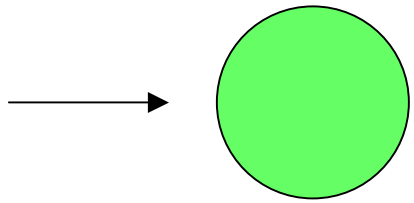
High Level View of Production Process

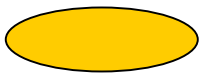
wafer

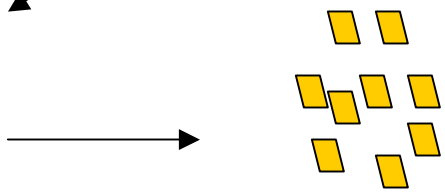




Reactor
- high pressure
- high temperature
- vapor density variations

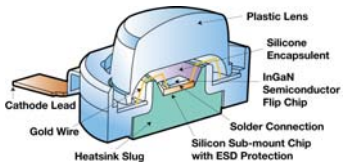
Finished wafer





Sliced and diced into thousands of chips or die

Packaging:
Die placement, wire bonds, encapsulation



Finished LED

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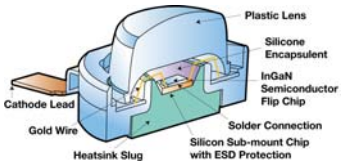
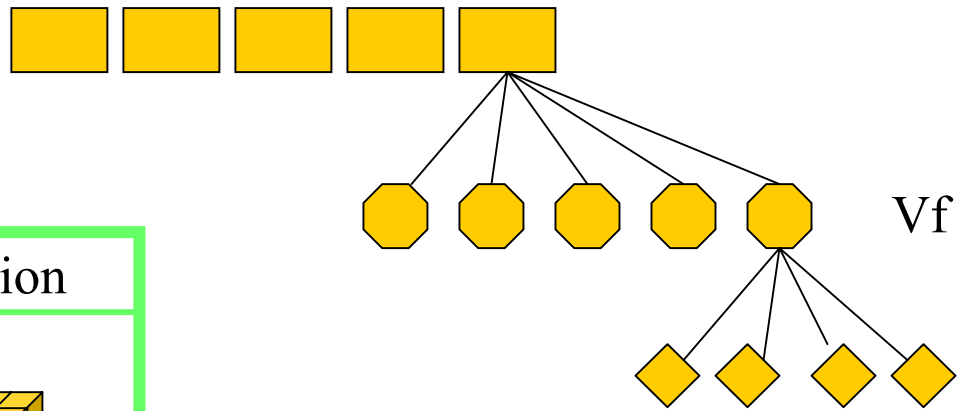
What is Binning?



Finished LED → 100% test

- Functional
- Color, Flux, Vf
- Each LED Labeled by bin

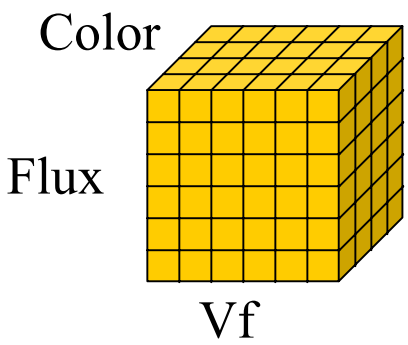
Wavelength bins, 2.5-20 nm wide



Vf bins, .20 -.50 mv wide

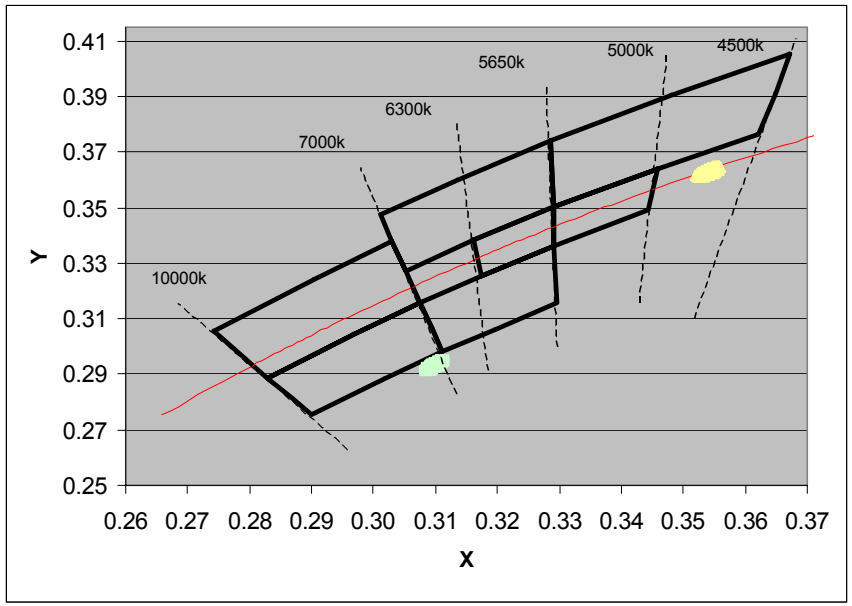
Flux bins: 30% + ranges

Full Distribution

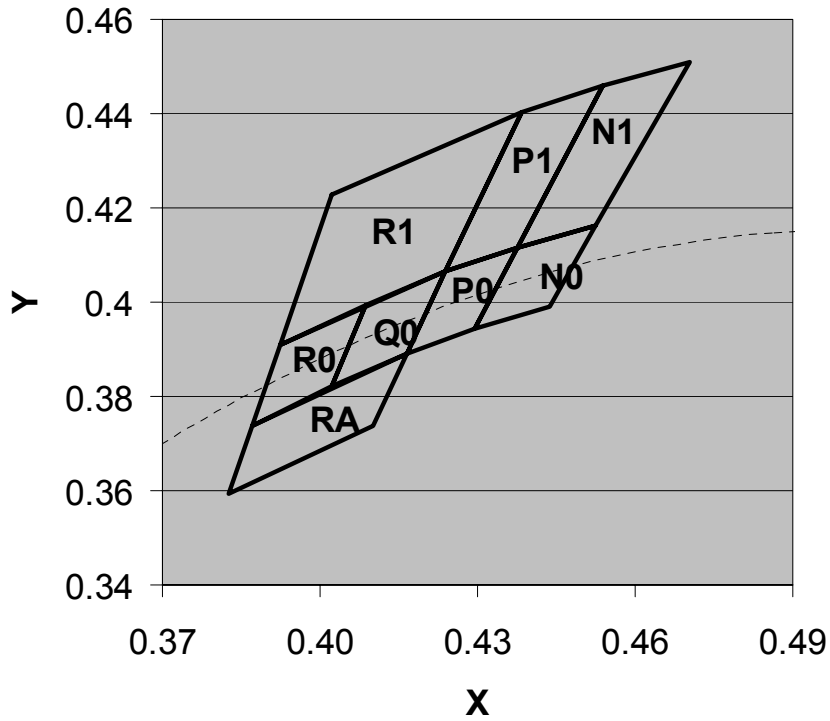


LUMILEDS

Better Binning - New



Cool White

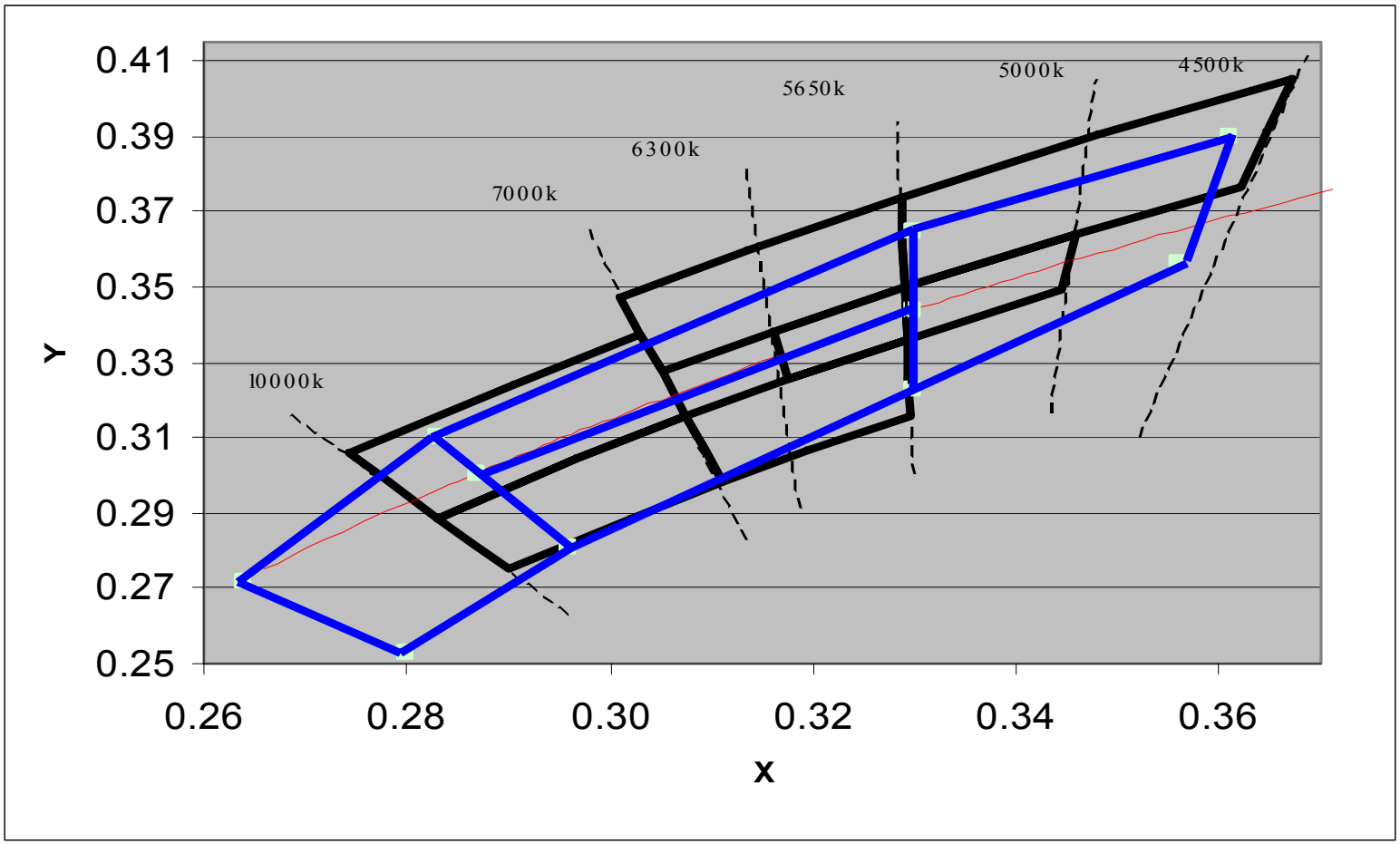


Warm White

LUMILEDS

Company B White Bins

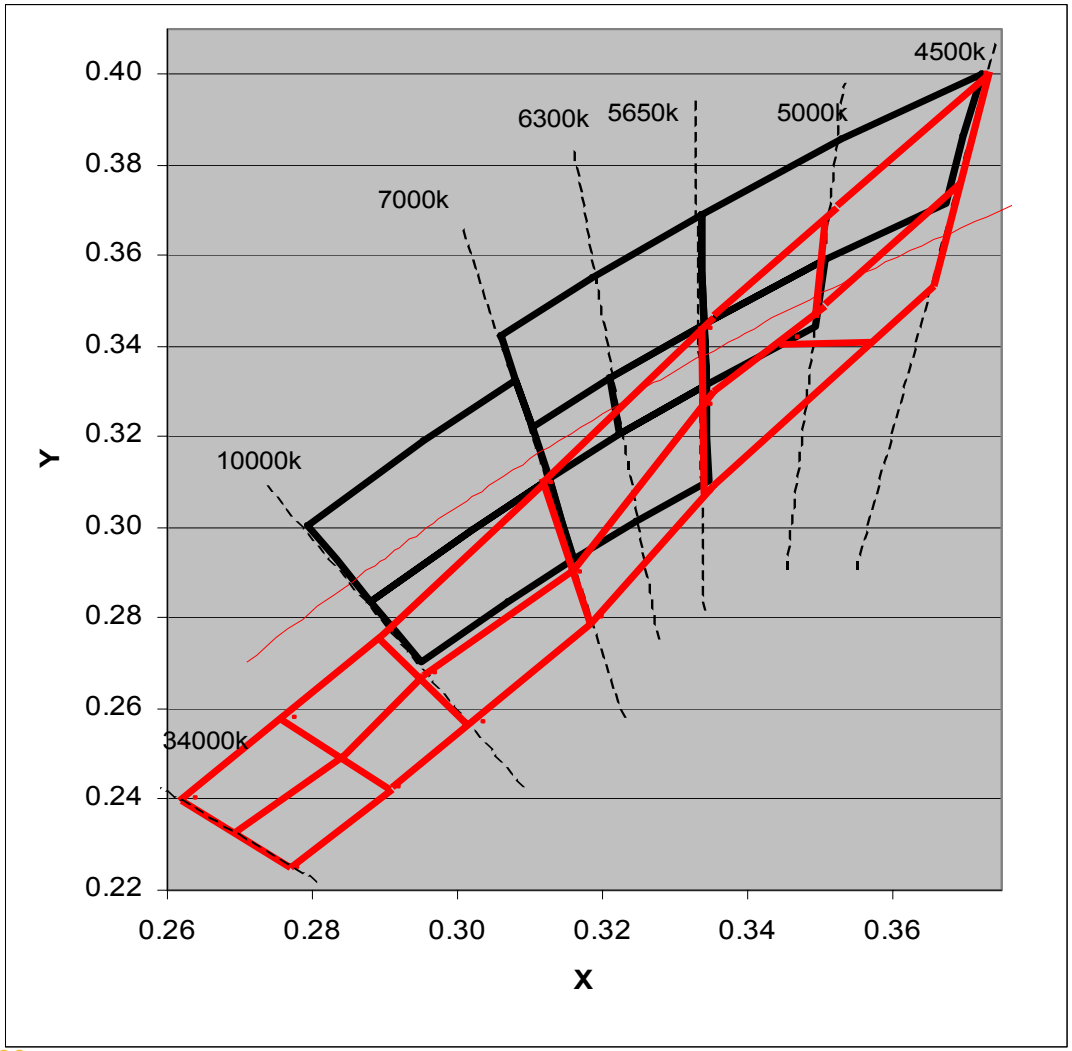
Company B bins are larger



Courtesy Lumidrives

LUMILEDS

Company C White Bins



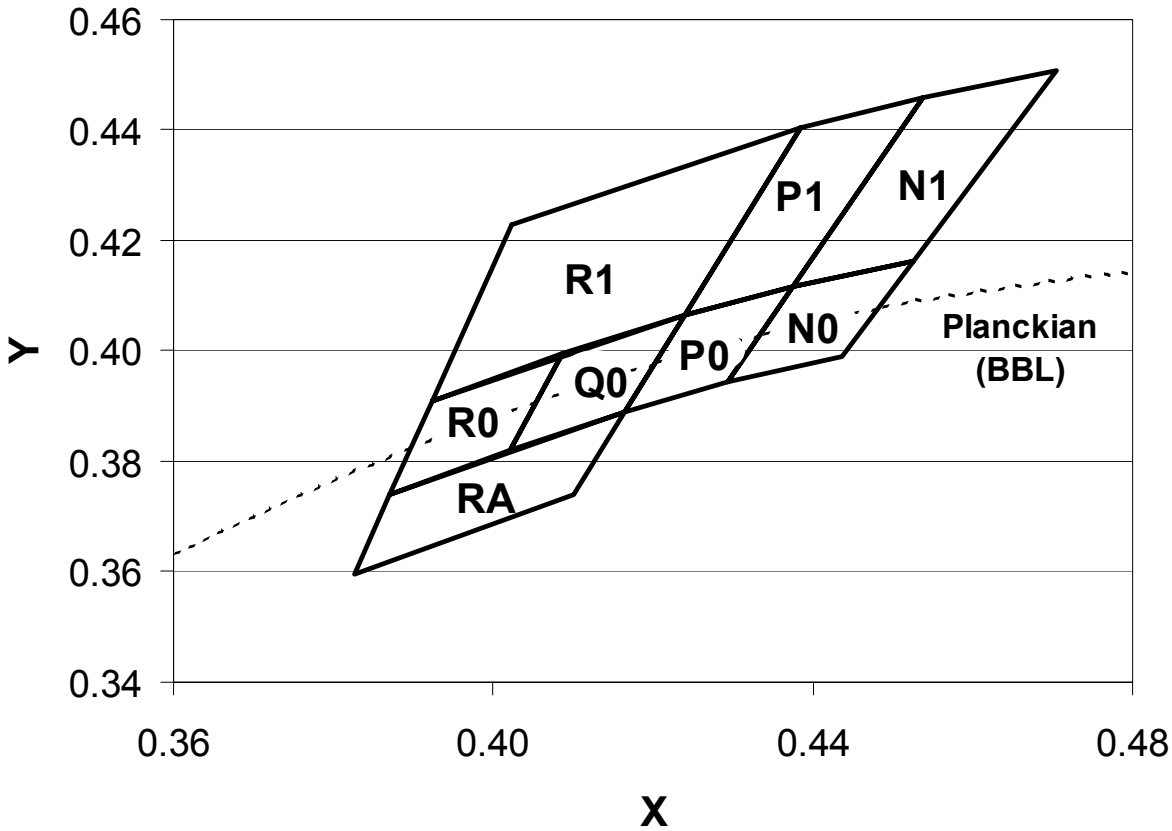
white bins average 8.5 step MacAdam ellipse

Company C bins are mostly below the Black Body Locus.

Courtesy Lumidrives

LUMILEDS

Warm White – Color Binning

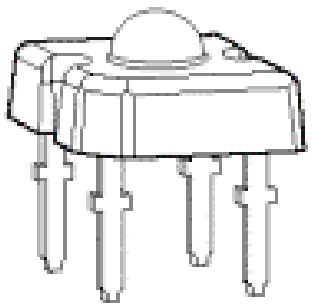


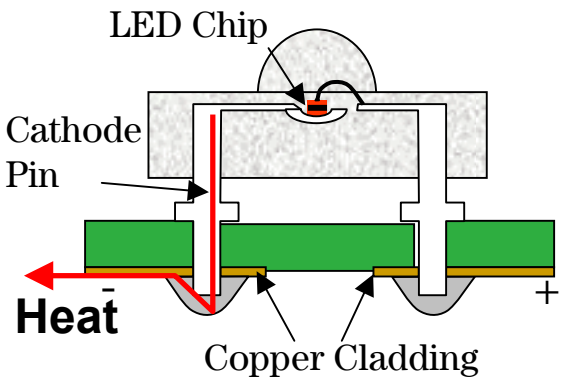
Bin code	Typical CCT (K)
N0	2950
N1	2950
P0	3150
P1	3150
Q0	3370
R0	3640
R1	3500
RA	3500

Tested and binned to fine resolution color binning structure to enable mixing and matching to achieve consistent color performance from the end product

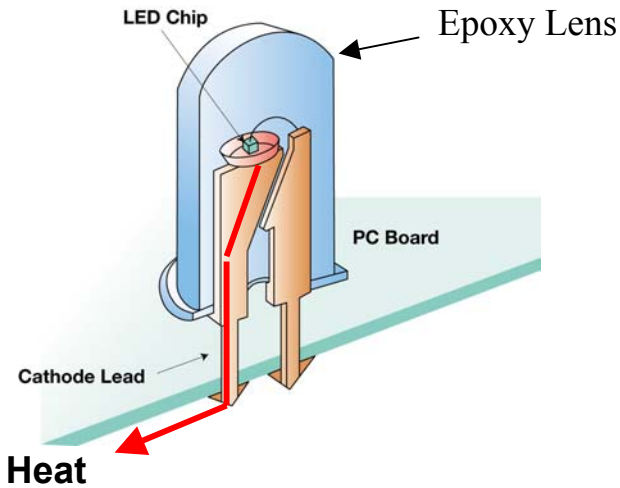
Packaging Technology – Low Power LED

- 5mm and SuperFlux combine thermal and electrical paths.
- SuperFlux added thermal conductivity.





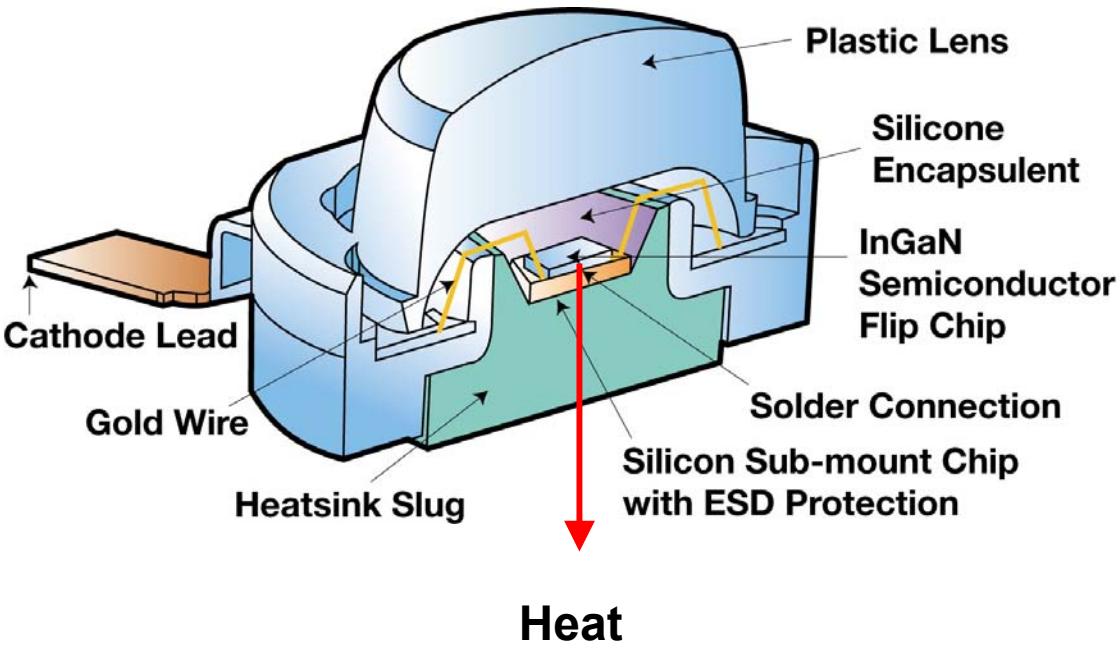
SuperFlux 2 Cathode Pins
Thicker Pins
Copper Pins

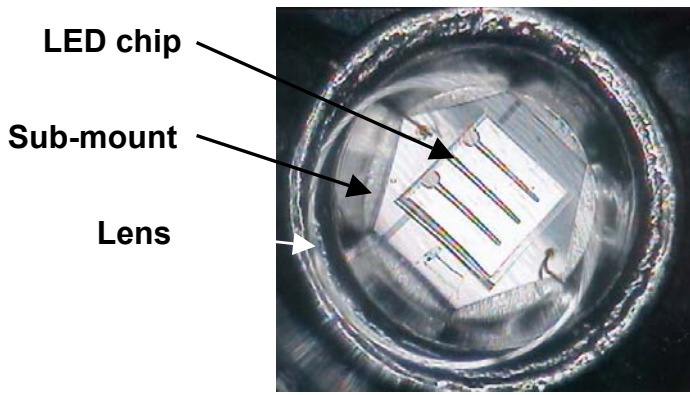


5 mm Lamp

Packaging Technology – High Power LED

- Dedicated heat conduction path, separate from electrical path.
- Excellent thermal performance matches demands of high drive currents.





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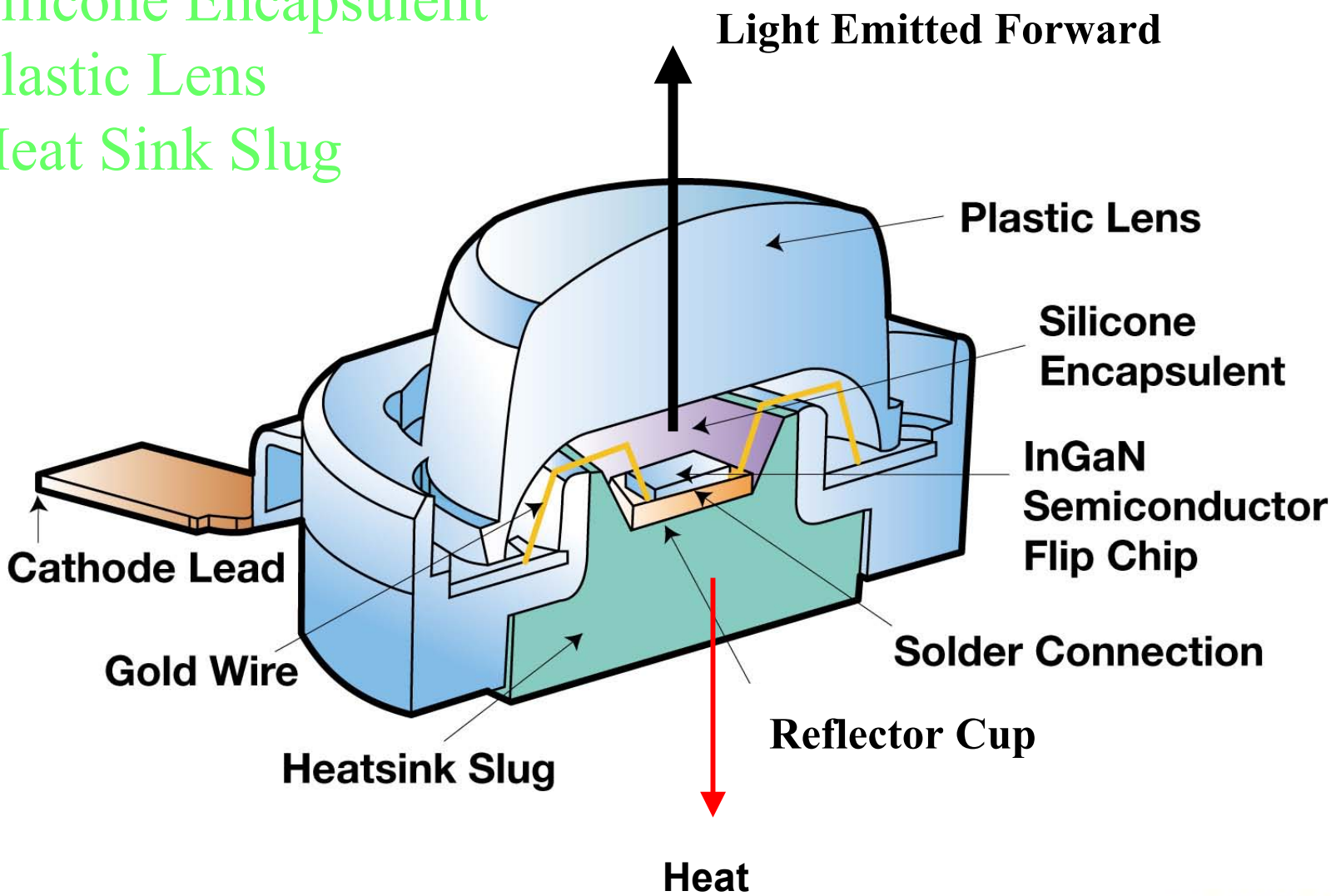
Packaging Technology - Better Life

1. Silicone Encapsulent
2. Plastic Lens
3. Heat Sink Slug



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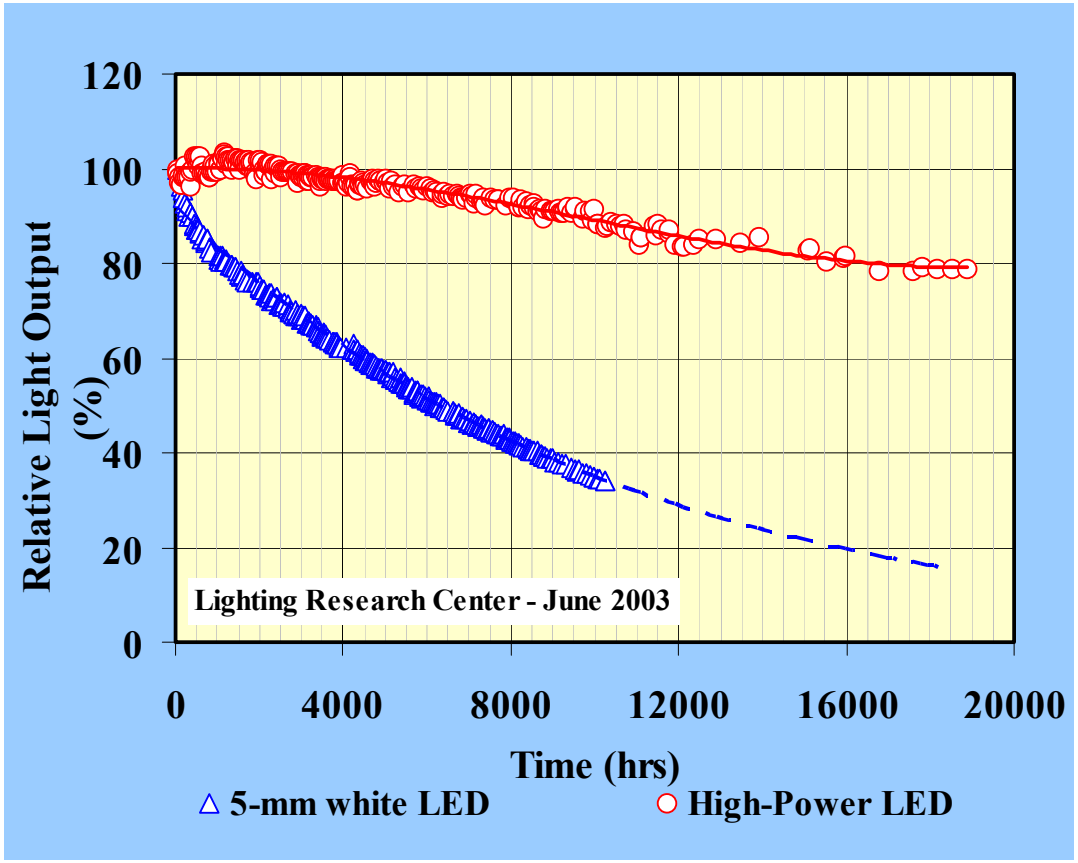
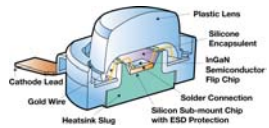
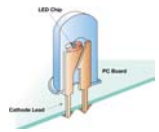
Packaging Technology – Better Life



High-Power LED



5-mm white LED



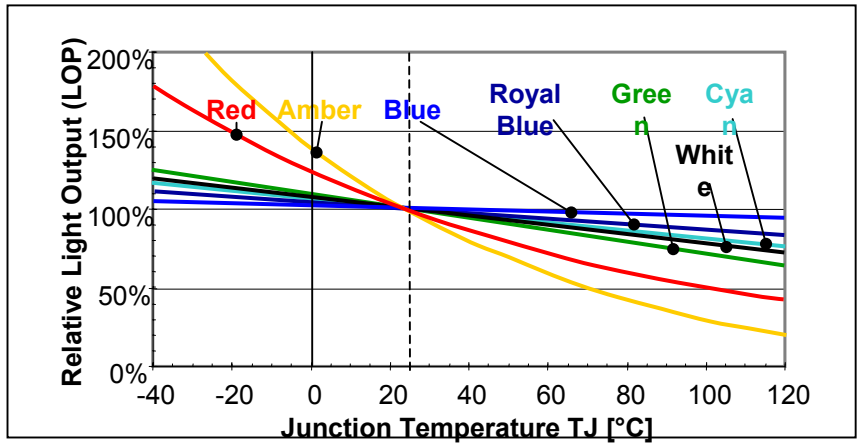
Courtesy Lighting Research Center

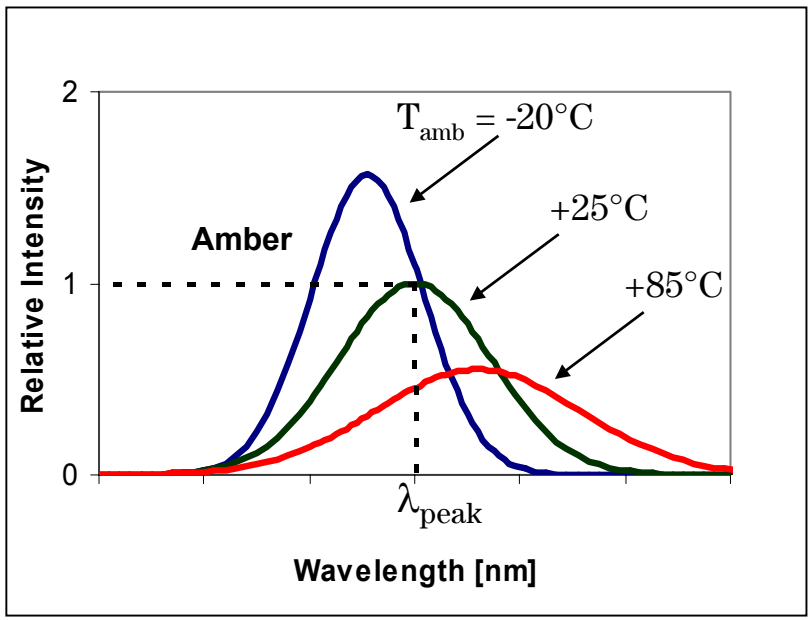
- Luxeon (colored and white) are rated for 70% average lumen maintenance (30% degradation) at 50,000 hours

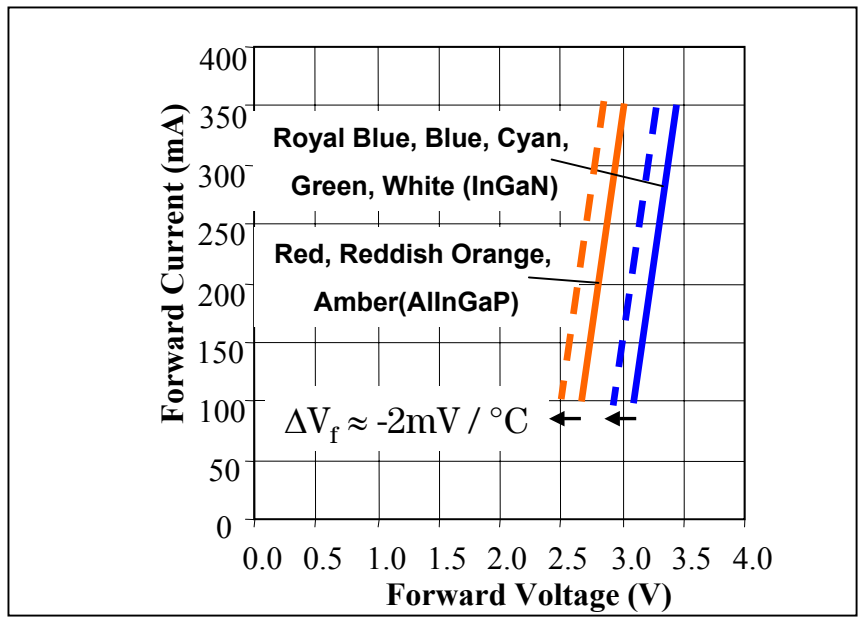
LED Parameter vs.Temperature

As temperature rises:

- Light Output decreases
- Wavelength gets longer
- Forward Voltage decreases







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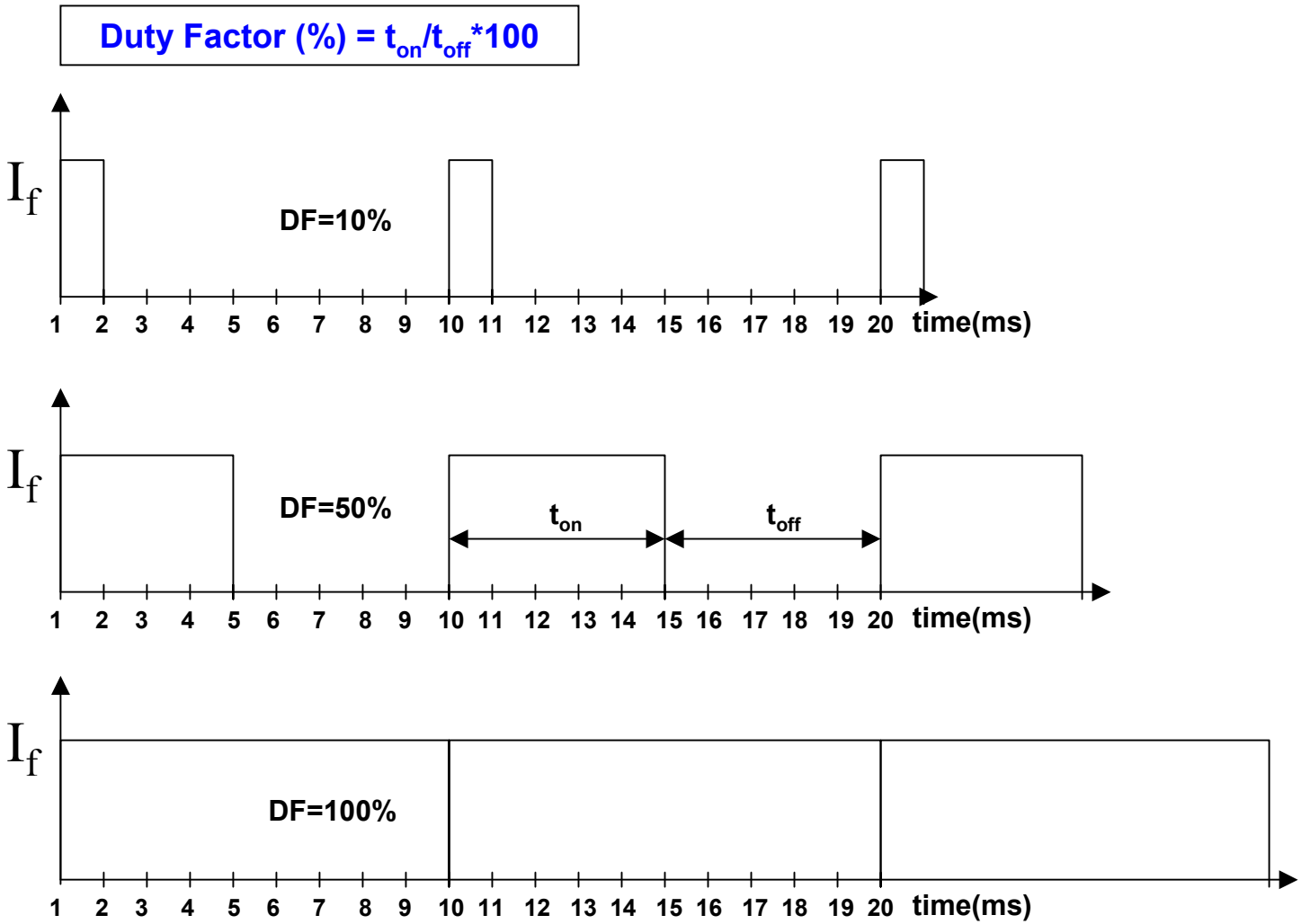
How is a LED dimmed? How are colors mixed?



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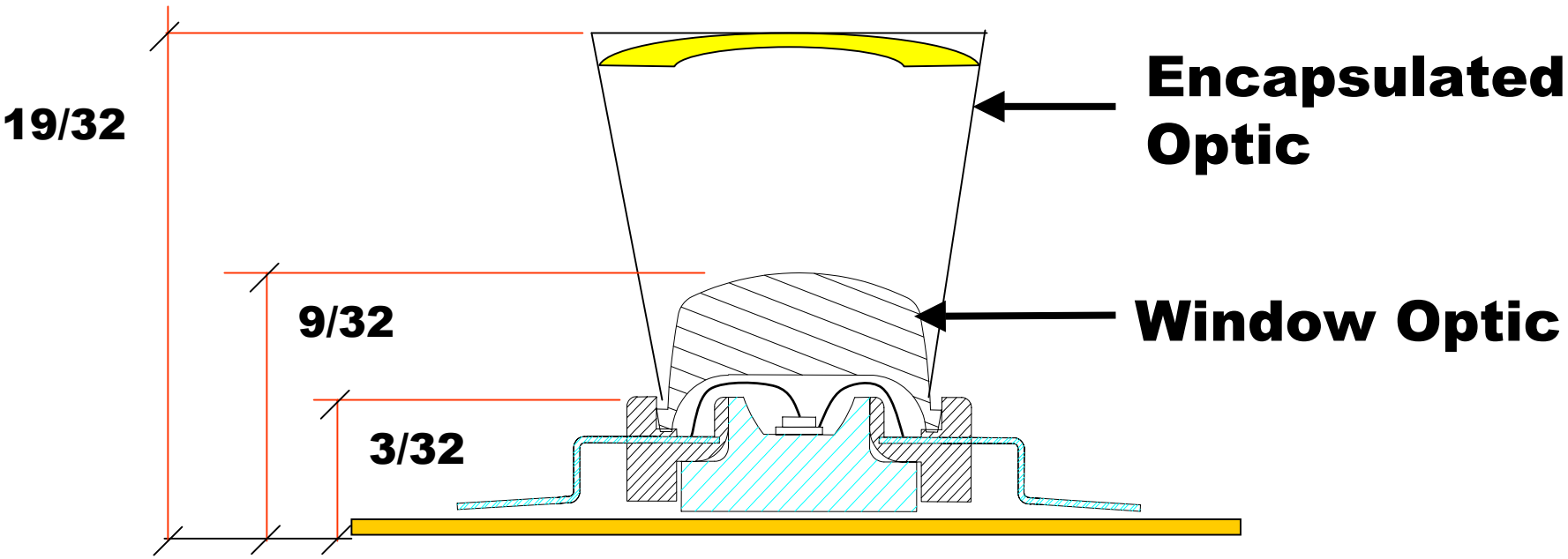
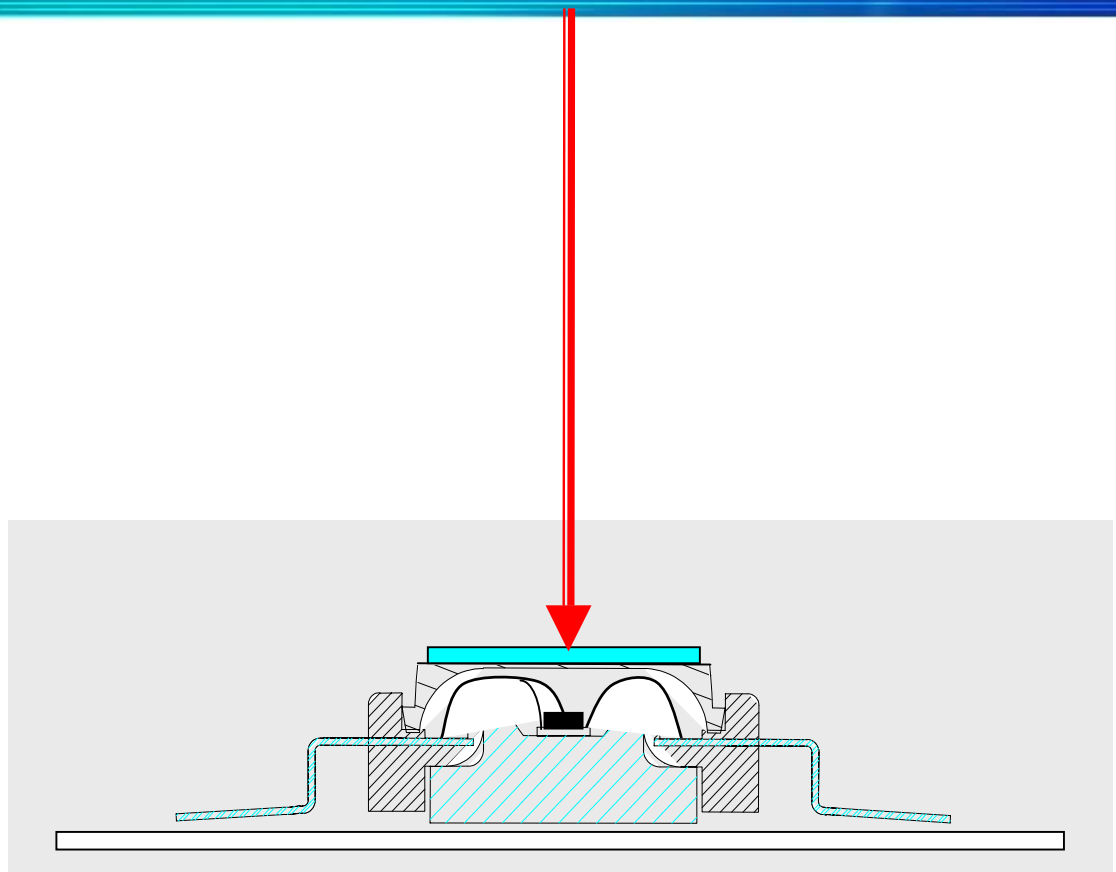
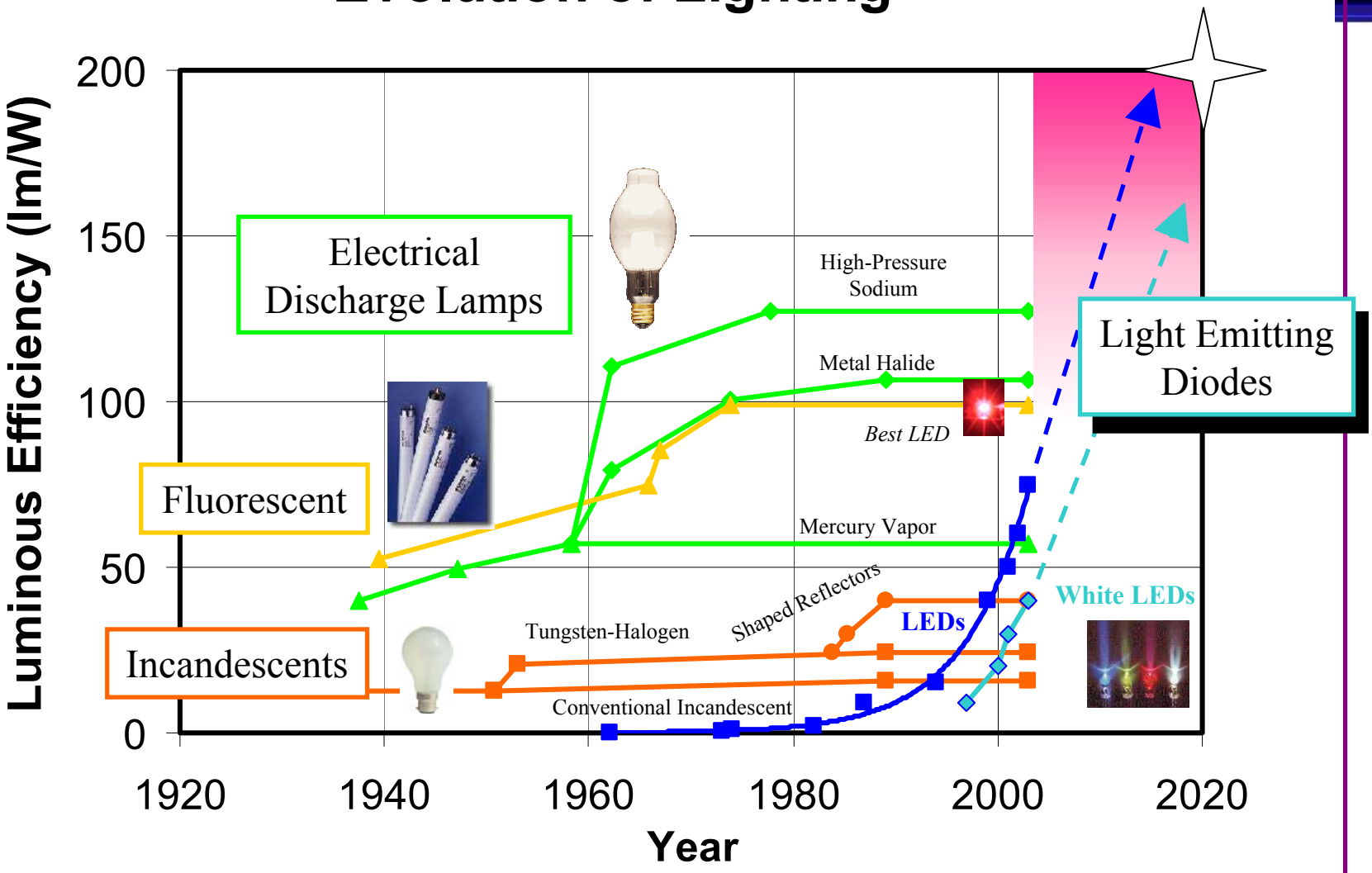
Encapsulated & Window Optics



Micro Optics ?



Evolution of Lighting



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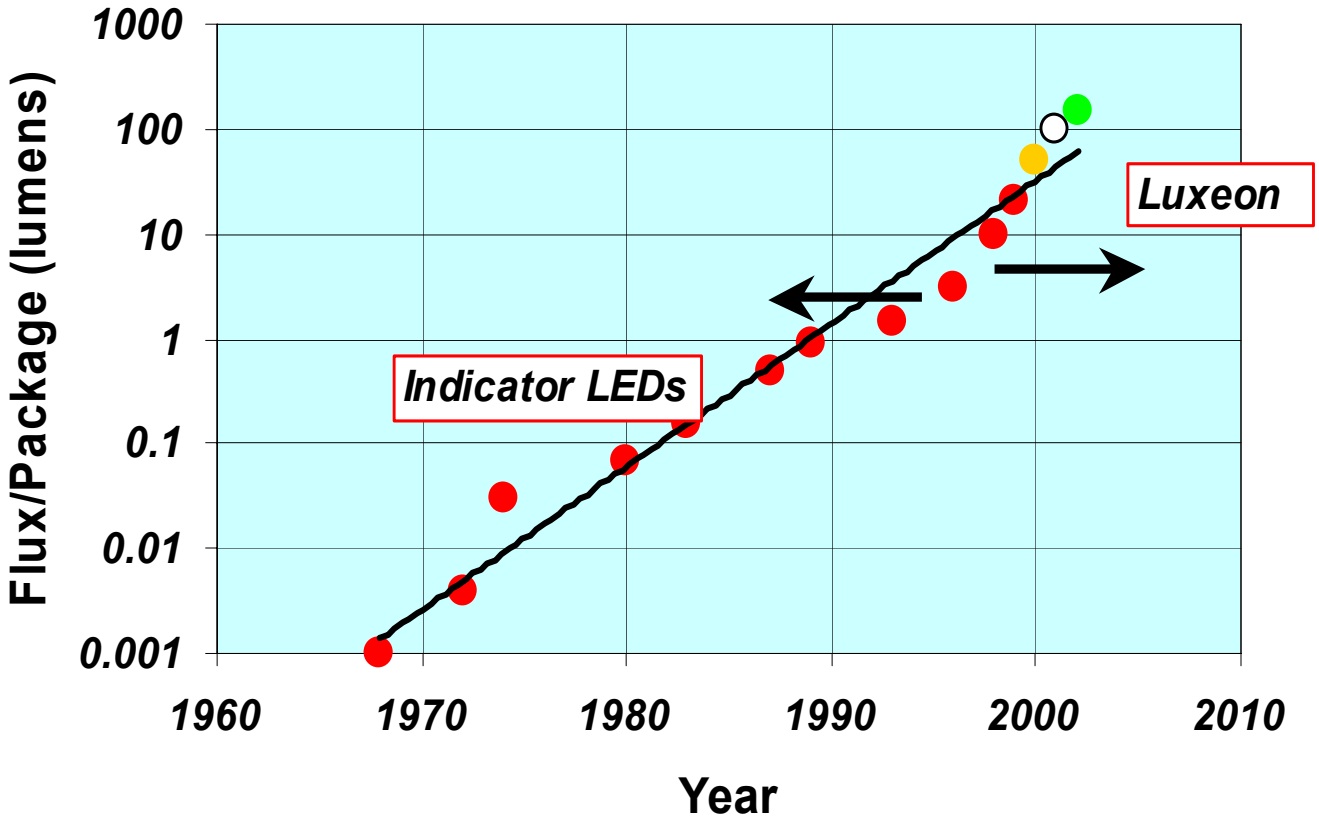
Evolution of LEDs

LED Flux per package has 35% per year for 30+ Years!!



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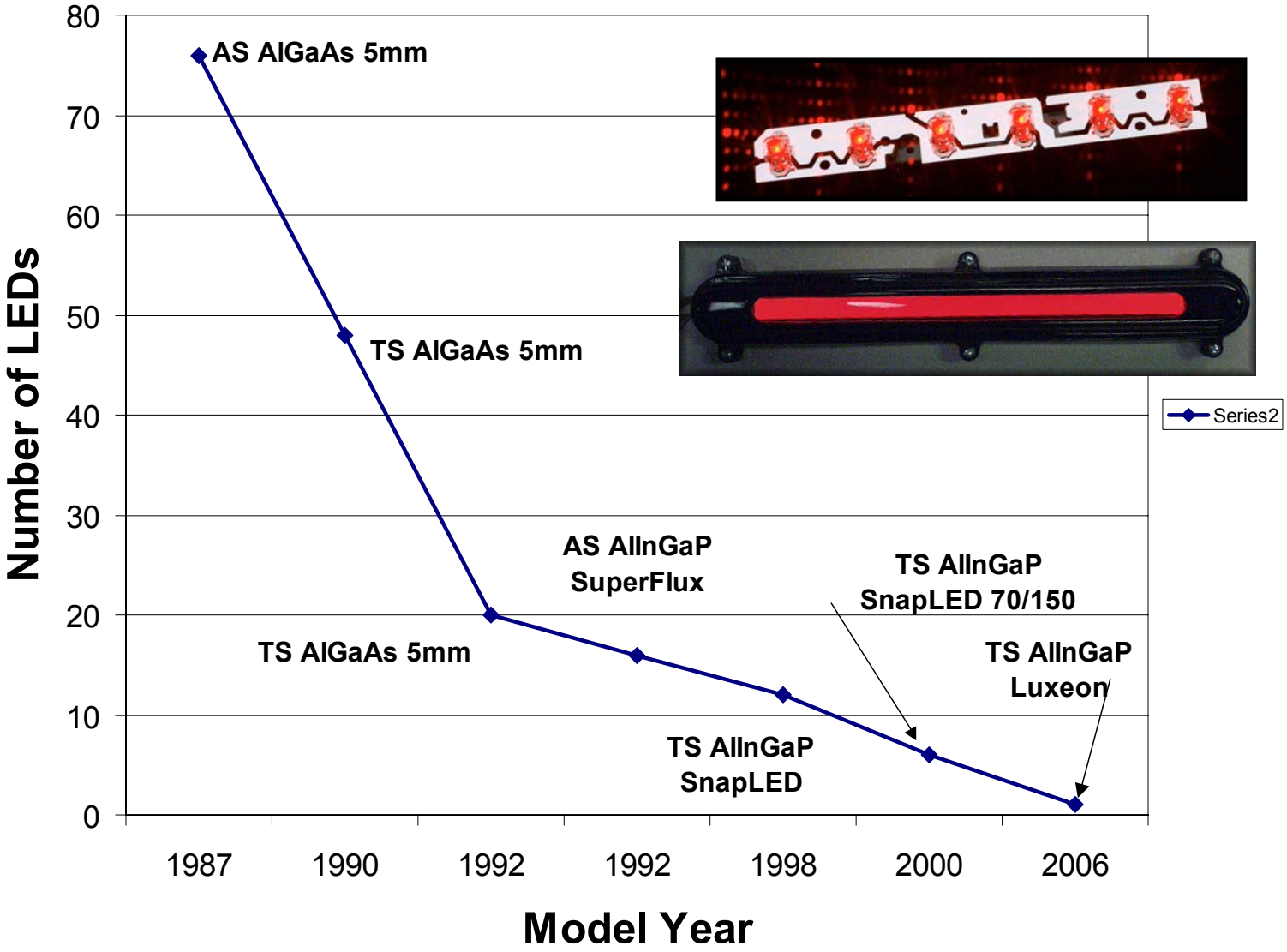
Evolution - Automotive CHMSL



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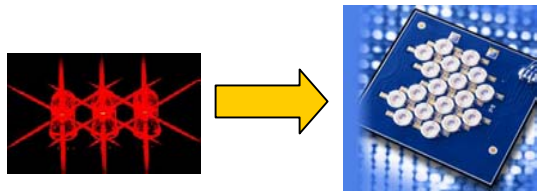
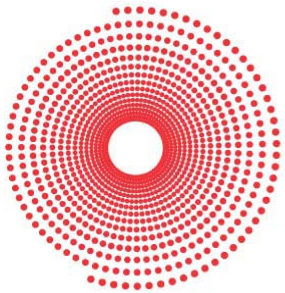
Evolution – Traffic Signal

Case in Point: …impact on Traffic Signals

5mm Thru-Hole to Surface Mounted

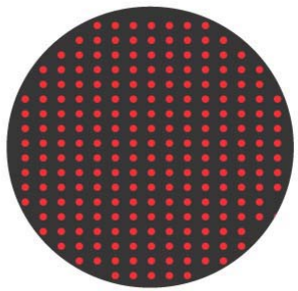


1993
5mm LED



700 LEDs

1996
5mm LEDs

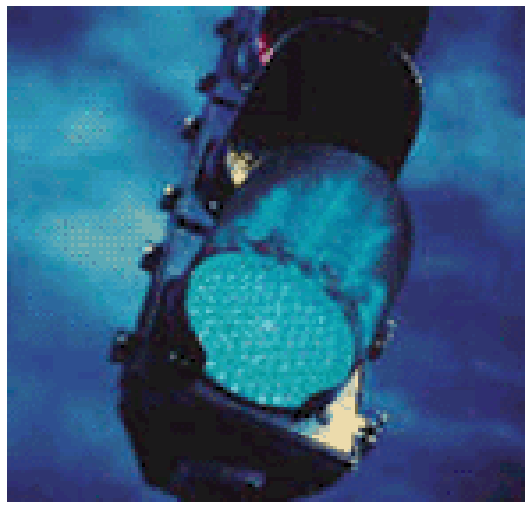


200 LEDs

1999
High Flux
Surface Mounted
LEDs

Lumileds Solution

18 LEDs
Red/Amber

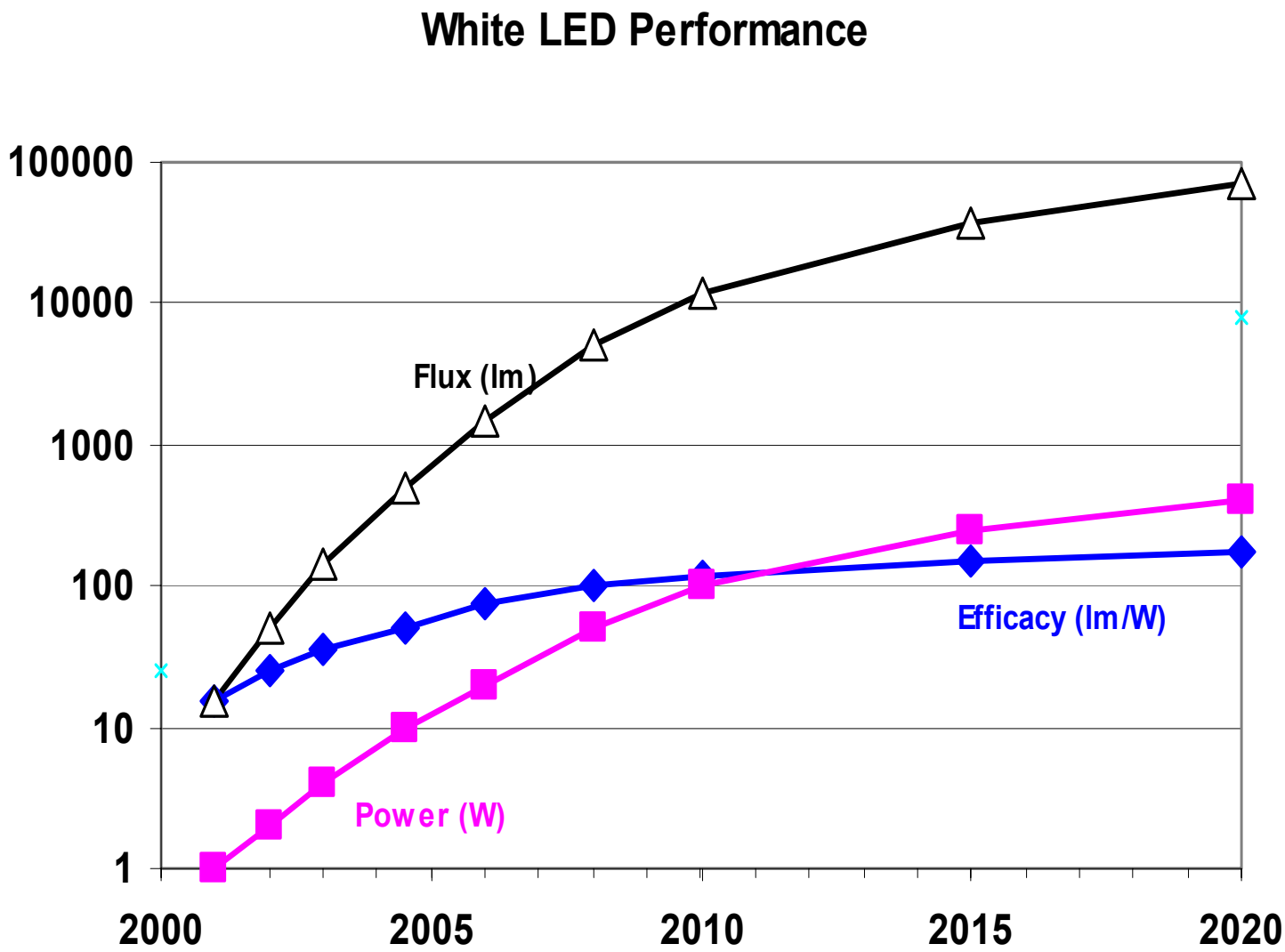


2003: 12 RED LEDs

Courtesy io Lighting

LUMILEDS

LED Technology



Courtesy Roland Haitz

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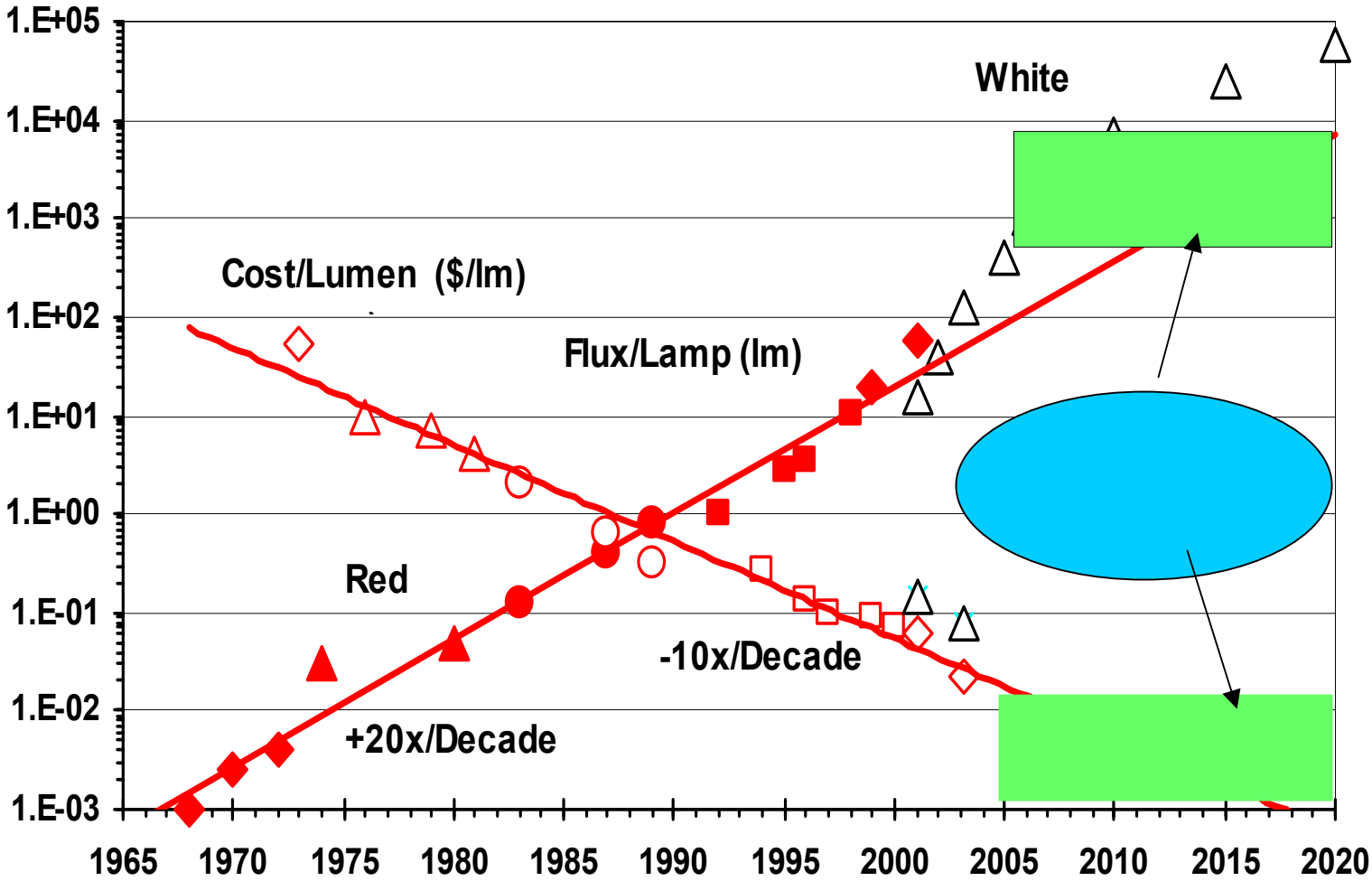
LED Technology
Flux/Lamp and Cost/Lumen



Courtesy Roland Haitz

LUMILEDS

Life Cycle Costs…

FRIDAY, AUGUST 30, 2002

FREDERIC LARSON / *The Chronicle*

Not much of a punch line here

How many Westin St. Francis Hotel maintenance workers does it take to change a lightbulb? Apparently, just the one who has the nerve to hang out over Powell Street at San Francisco's Union Square in order to get the job completed. When he gets done there, there are plenty more lightbulbs to be attended to - the hotel has a total of 1,194 hotel rooms including 84 suites.

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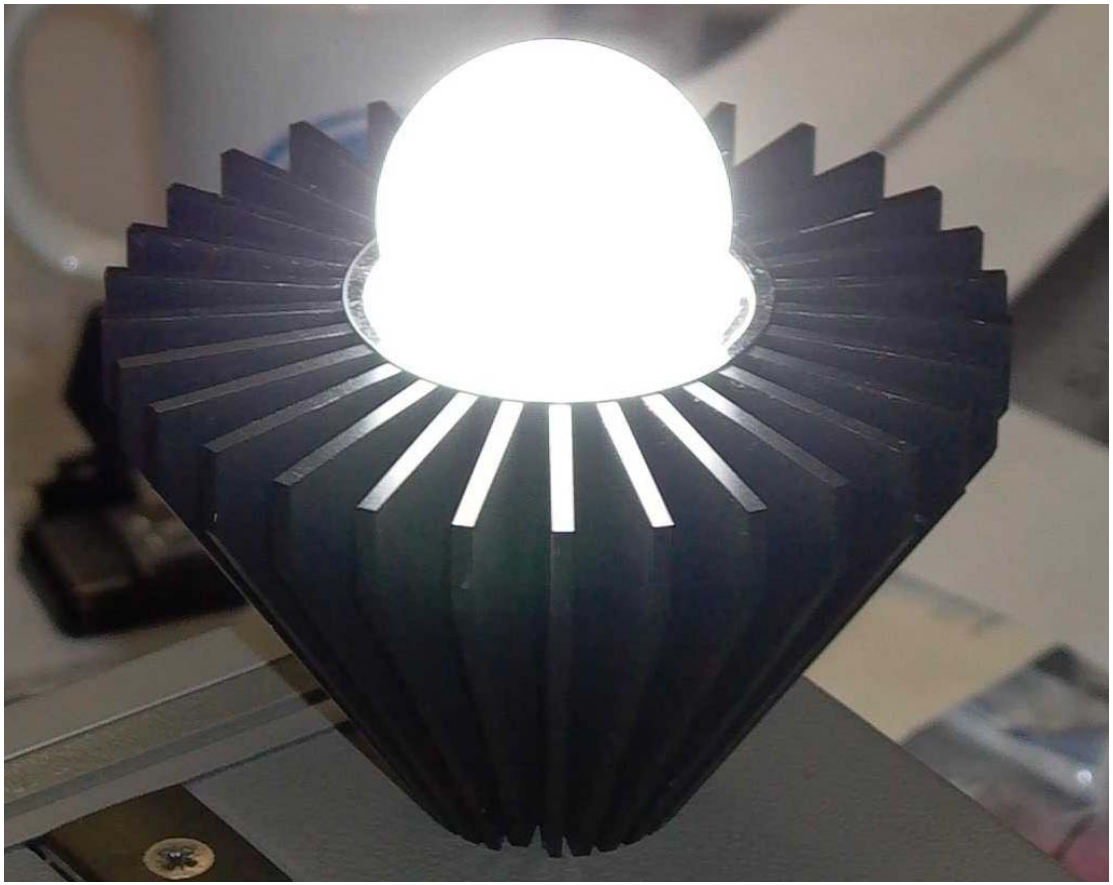
Future Developments



- *>500 lumens*
- *5700K CCT*

- *>500 lumens*
- *3500K CCT*

LED Technology Summary

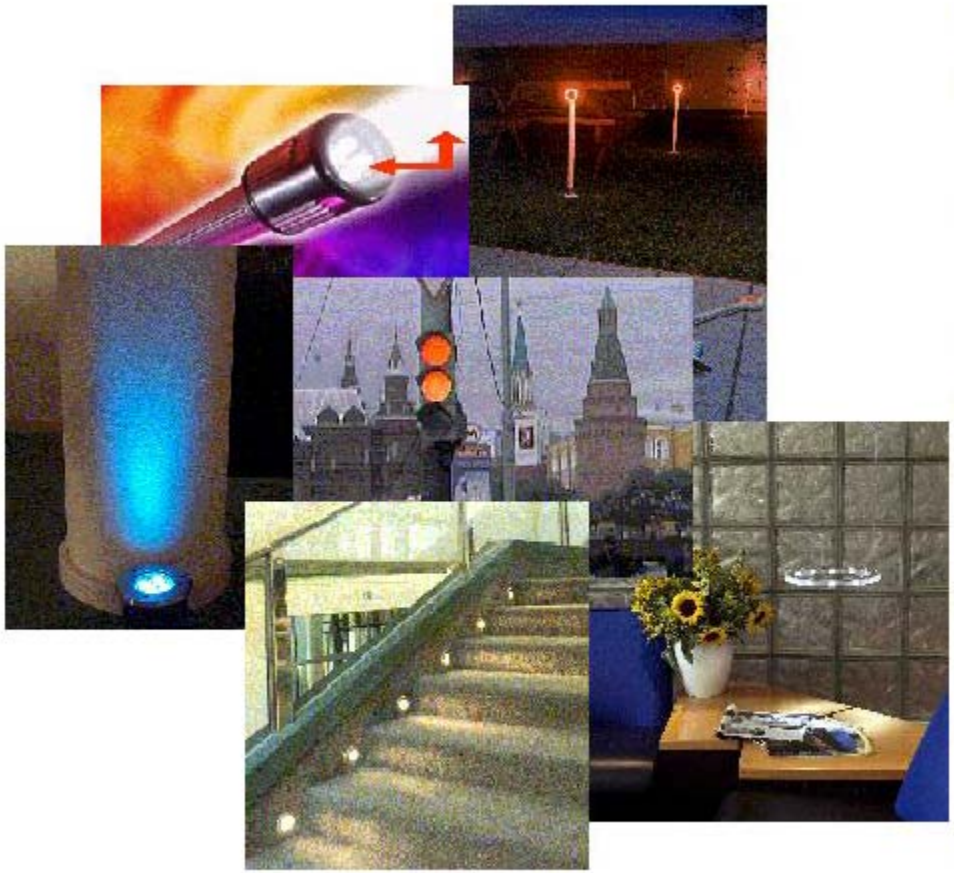
- **Colored Lighting:**
  LEDs are a disruptive technology replacing conventional sources and enabling new applications. LEDs should dominate these markets due to their efficiency, design flexibility, and reliability
- **Low Power White Lighting:**
  LEDs are moving into a wide variety of niche applications. LED market penetration will accelerate as higher efficiency LEDs with better color rendering become available, and within the next 5-10 years LEDs should dominate.
- **General Illumination:**
  Efficiency and cost breakthroughs must be achieved to enable LEDs to substantially replace conventional lighting. Performance of 150+ lm/w and 100x lm/w cost reductions seem possible over the next 10-20 years. This would result in LEDs being a disruptive technology for all existing lighting technologies and will enabling new applications and approaches to illumination infrastructures.

Presentation Agenda

- Introduction
- Solid State White Light
- Technology
- **Luminaires and Applications**
- Integration

SSL Applications Enabled Today

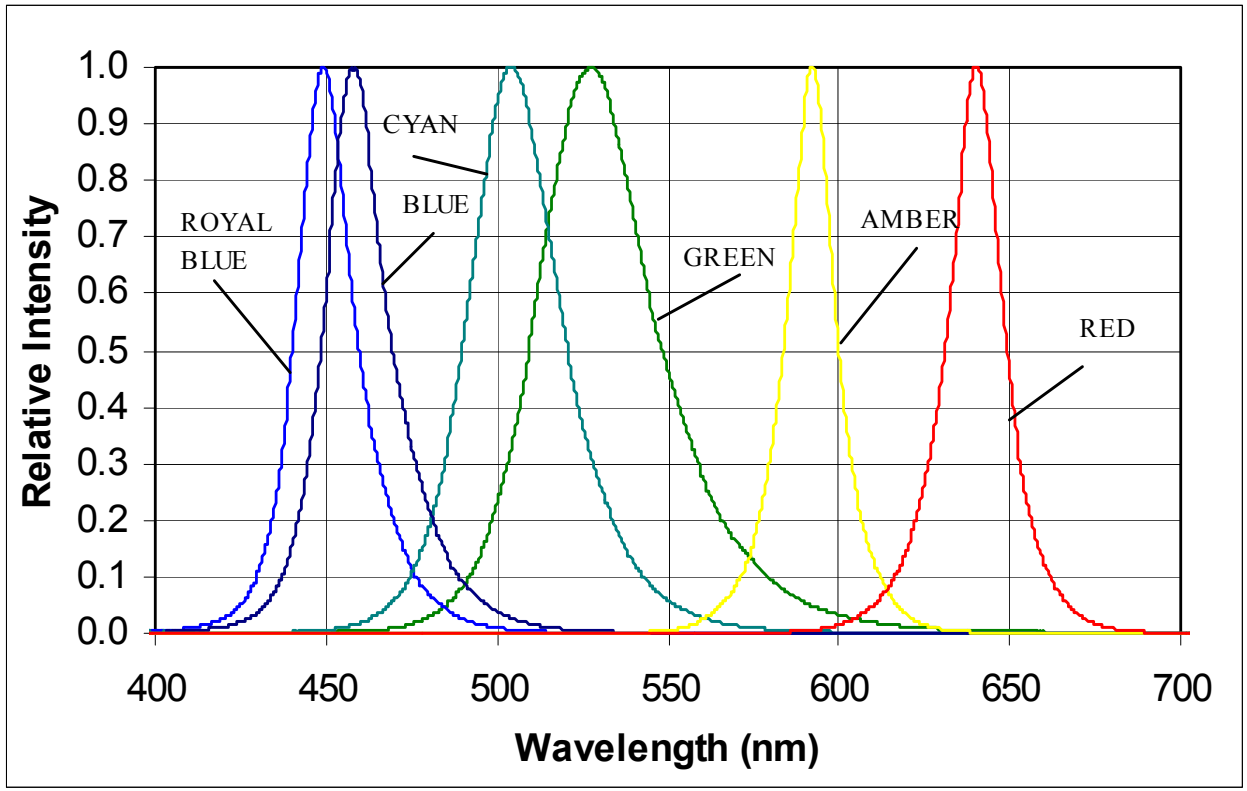
Lighting the World with Semiconductor Technology



- Traffic / Railway / Marine / Airport Runway Signaling
- Automotive Exterior / Stop-Tail-Turn / CHIMSL / EVL
- Signage / Corporate Identity
- Portable Lighting / Flashlights
- Low Lumen Accent / Reading / Map / Task Lights
- Stair / Step / Orientation Lighting
- Fiber Optic Alternative
- Landscape Lighting / Bollards
- Architectural Detail / Column / Wall Wash / Cove Lighting
- LCD Back Lighting / Edge-Lit Signs / Point Of Sale

In the Beginning…

We started with colors



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“Luminance” type applications

LEDs produced enough light to be seen but were still not being used to illuminate

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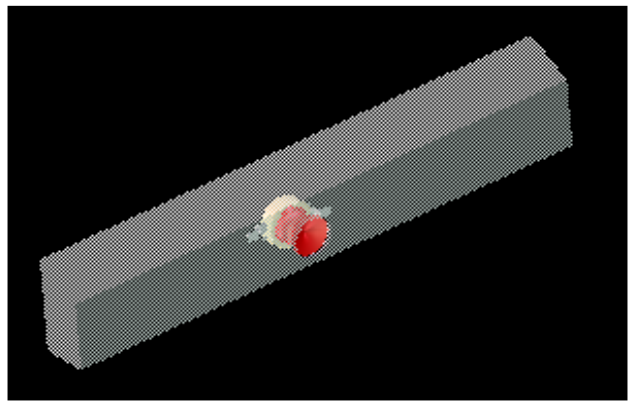
Edge Lit into Acrylic*

Single LED Exit Sign

- 1 Red Side-Emitting Luxeon Emitter
- Excellent in-coupling into acrylic with a single blind or through hole



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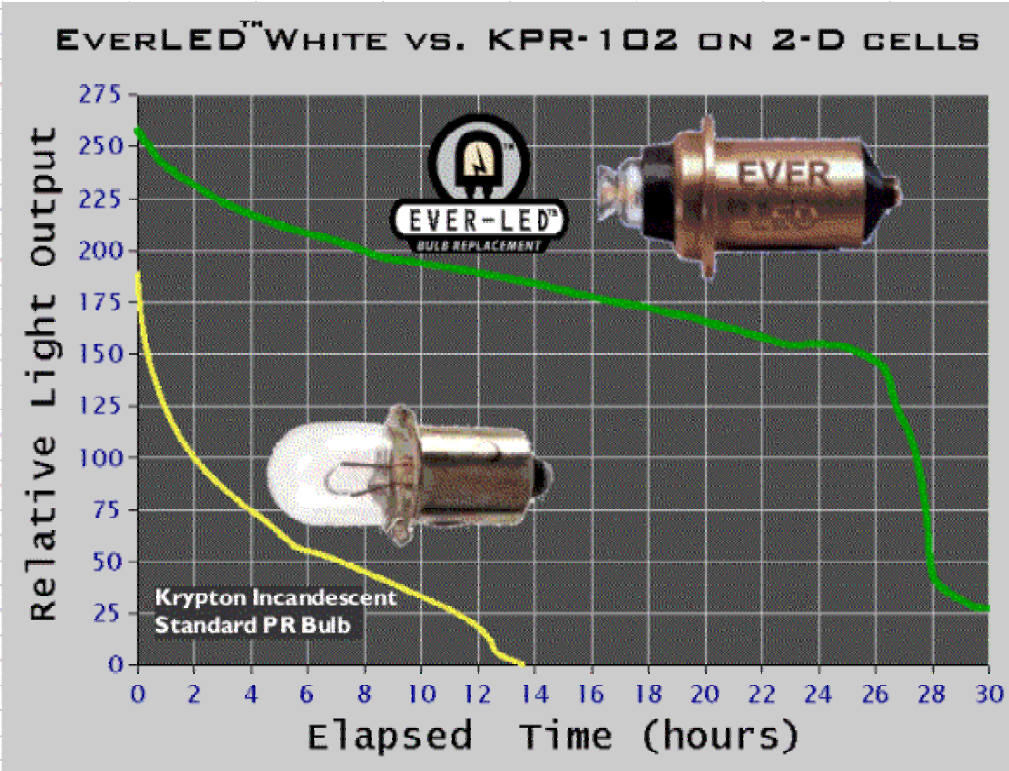
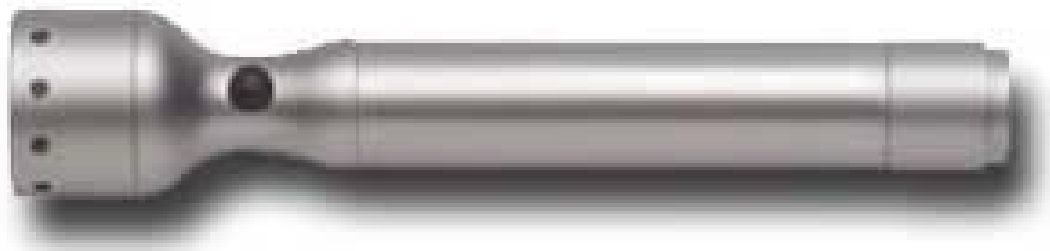
Portable Lighting





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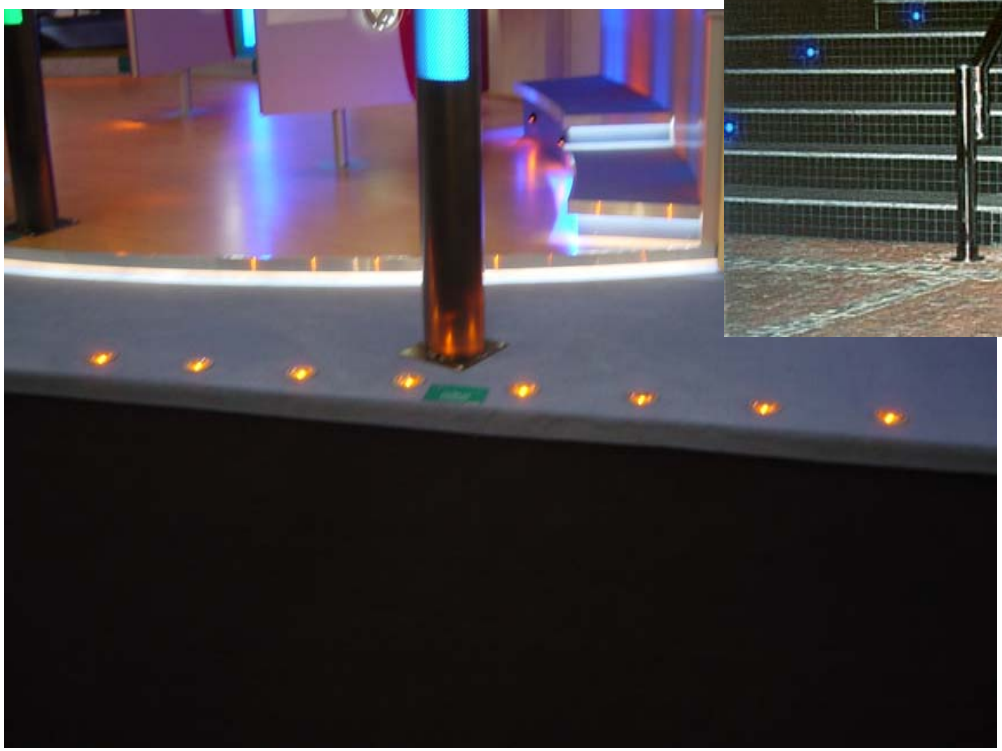
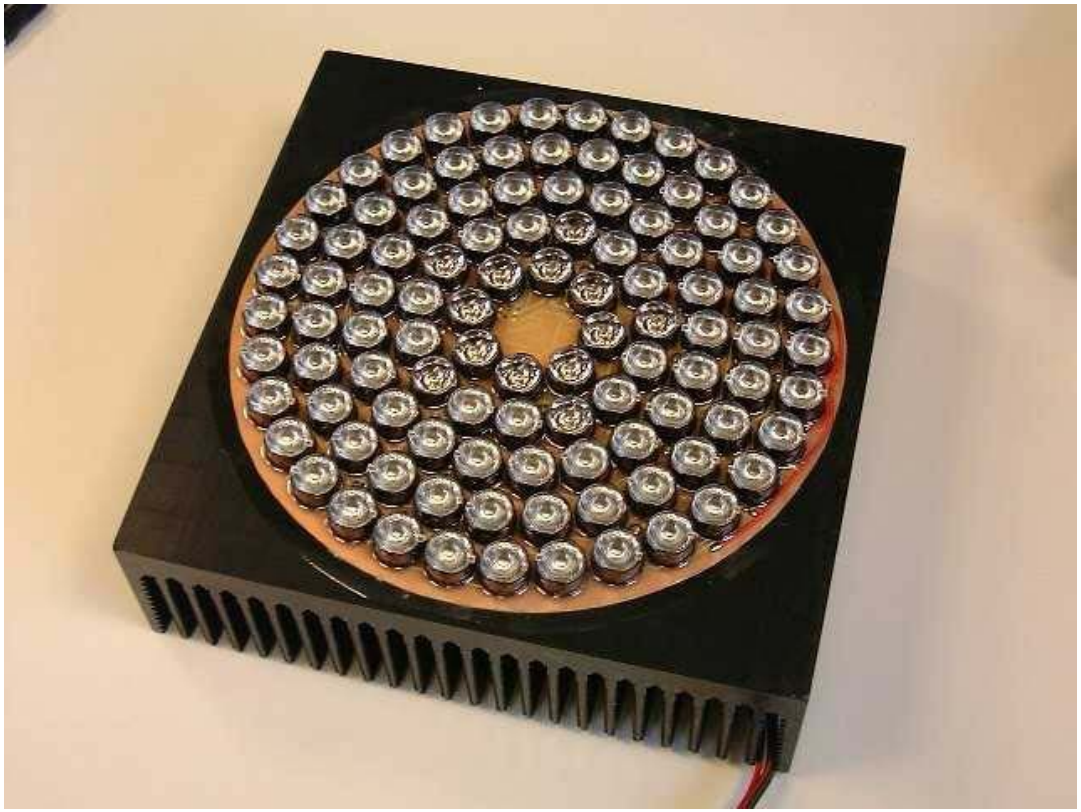
Safety and Step Lighting



Emergency Lighting

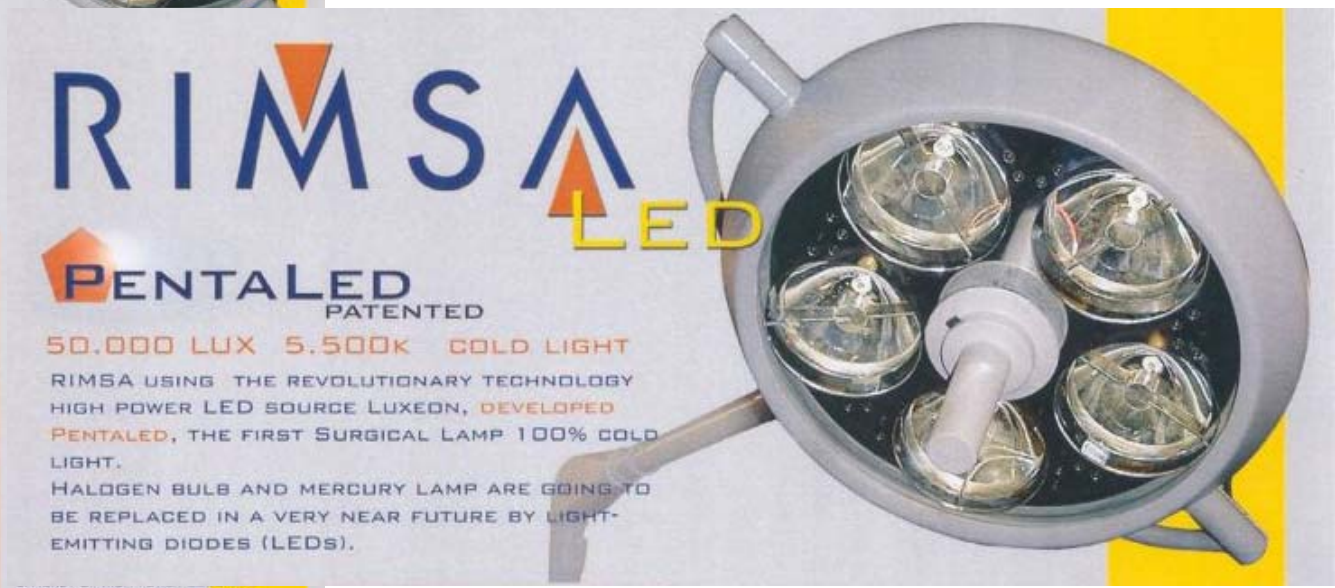
Emergency Lighting
Luxeon White side emitter
1 Watt power

Navigation



Harbour / Dock light – 1 mile visibility
Red
Energy efficiency, reliability, maintenance

Medical



Operation Lamp
Luxeon V White Side emitter
Cold Light, no UV/IR

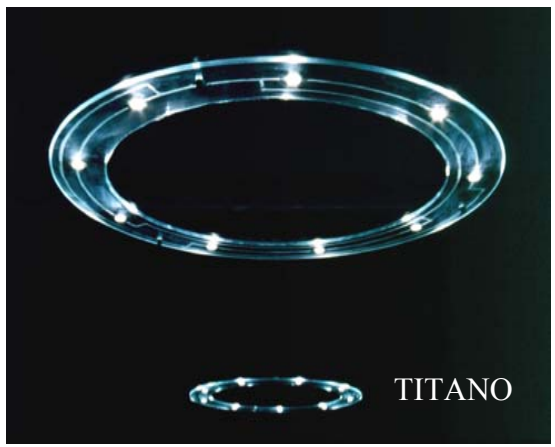
A New World of Luminaires

LUMILEDS

Task Lighting

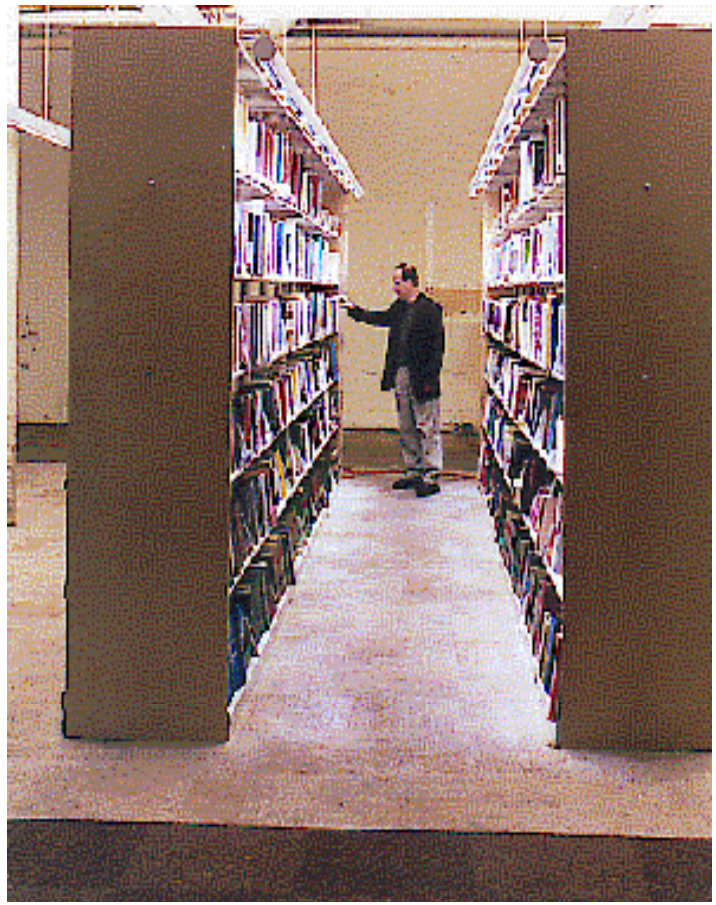
Table lamp
Luxeon White w. optics
4 Luxeon per lamp

Pendant



Cove Lighting*

Under/Over Cabinet Lighting



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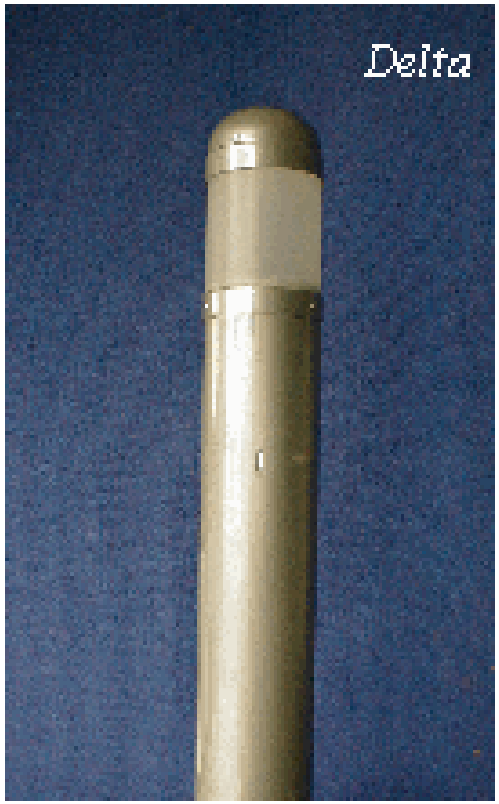
Landscape



Bollards , Small street poles

Low voltage wiring, Energy efficiency, reliability, maintenance

Deltalux - Sweden

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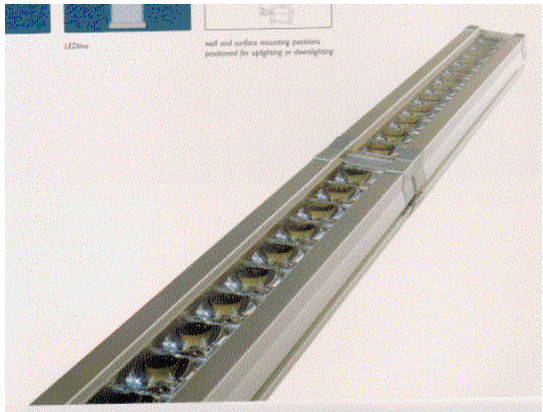
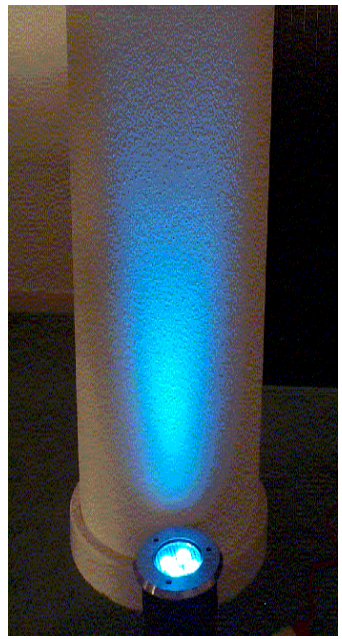
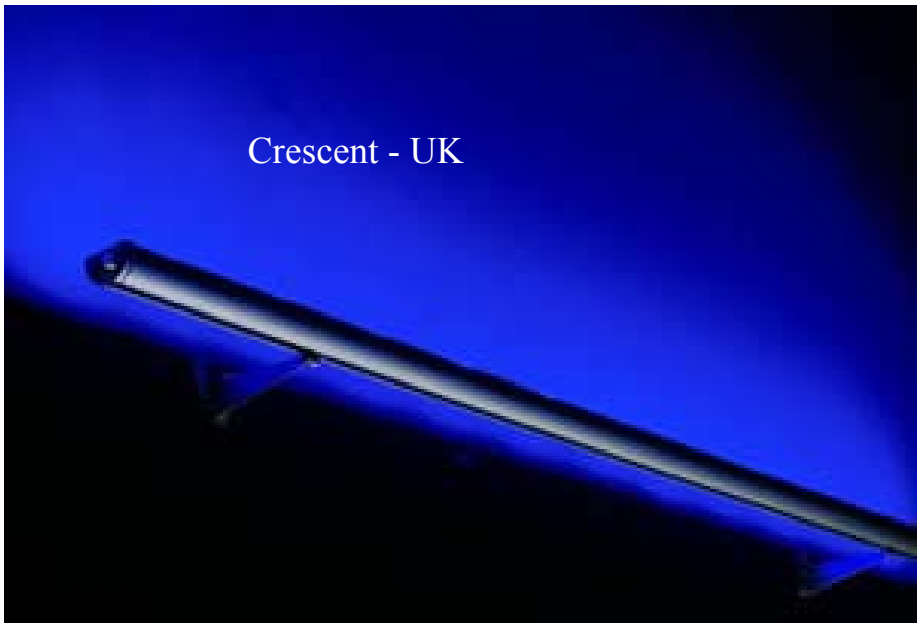
Sconces and Wall Wash

Wallwashing







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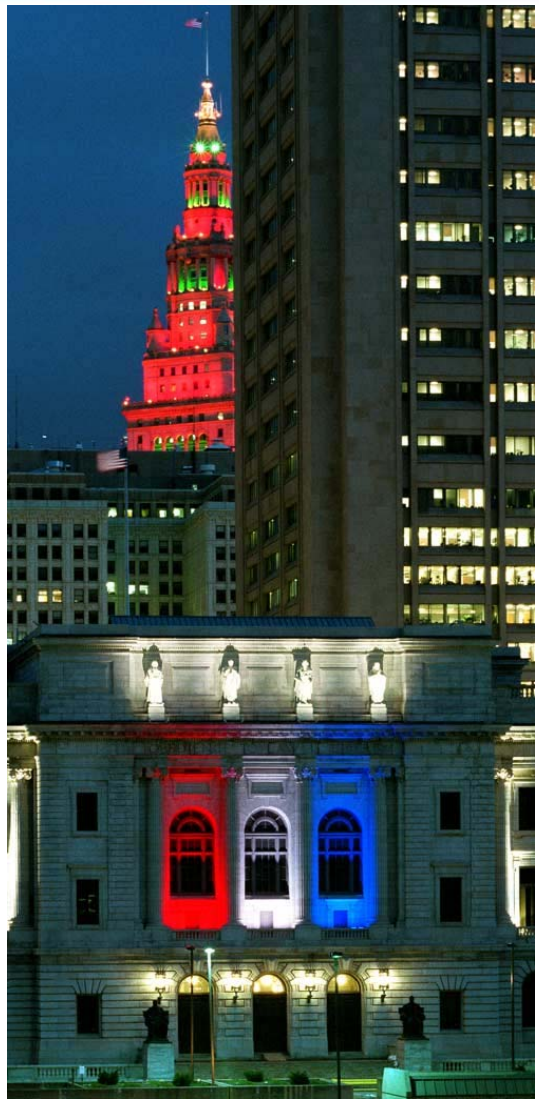
Wall Washing

Philips Luminaire - France



Color Kinetics

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Add Power and Dynamic Control

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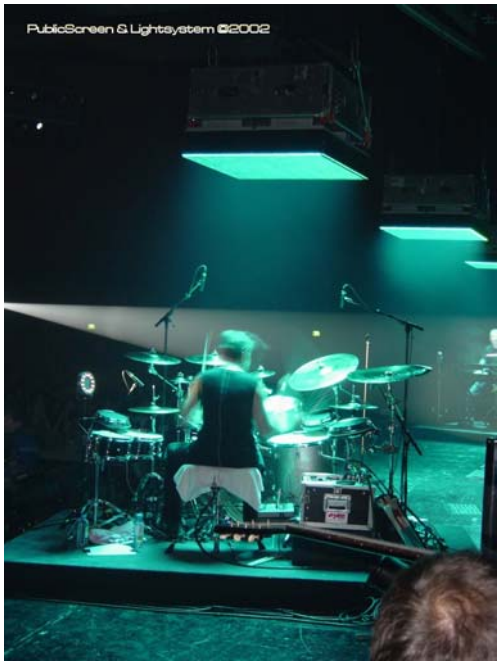
And Create ….



Herbert Groene concert tour - Germany

Dancefloor in The Netherlands

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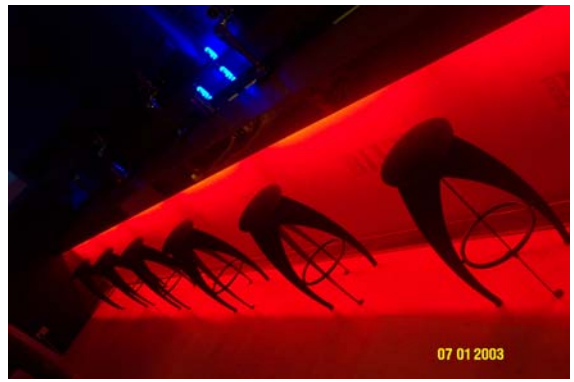
Club Lighting

Wall washing moves inside with color changing



Bar Blue – Felixstowe – UK

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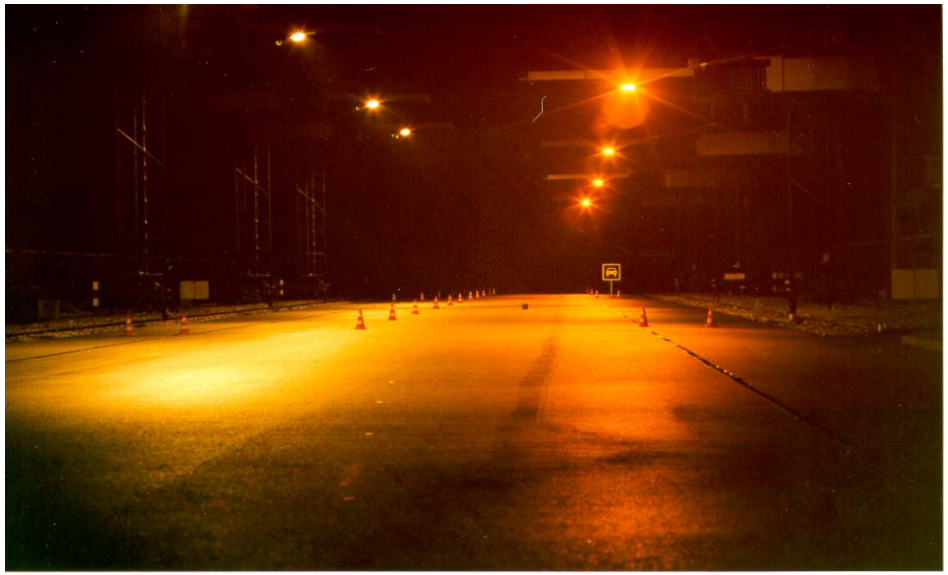
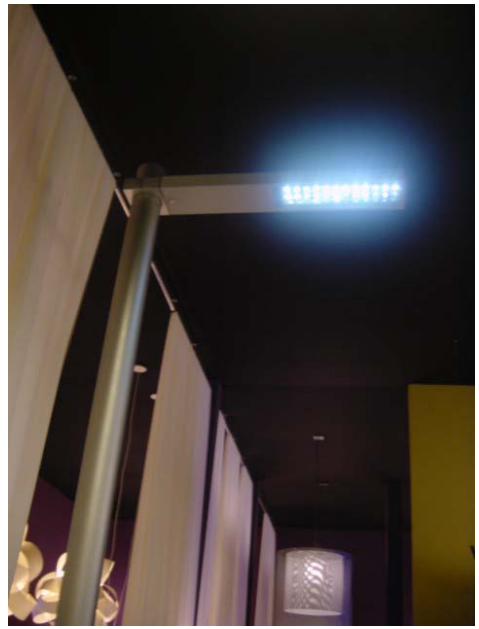
Street and Roadway





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Escalator Lighting

Taipei Municipal Social Education Hall/Taipei Culture Center

2004 IIDA Special Citation Award

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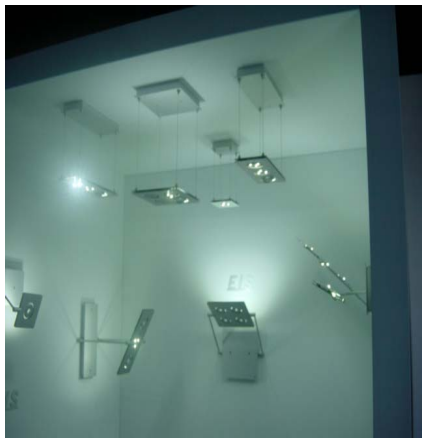
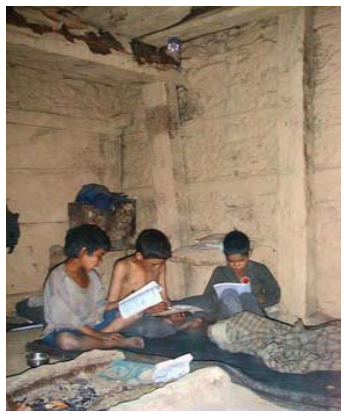
Residential Lighting Applications



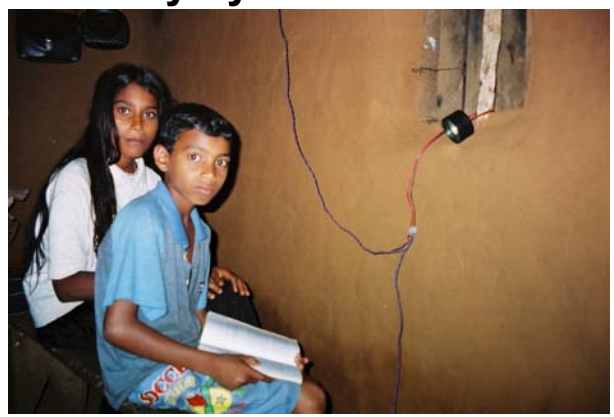
Lamps based on Luxeon White 1W

Apartment lit solely by Luxeon LEDs



Nepal 2000*

India 2001*



Sri Lanka 2003*

* Photos Courtesy of Light Up the World and PICO Power

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Retail Lighting

High Power LEDs emitters 3200K, 90CRI warm white
4 units x 32 pcs.

…with colored backdrop

Luxeon emitters Red, Green, Blue

12 pcs. Per unit

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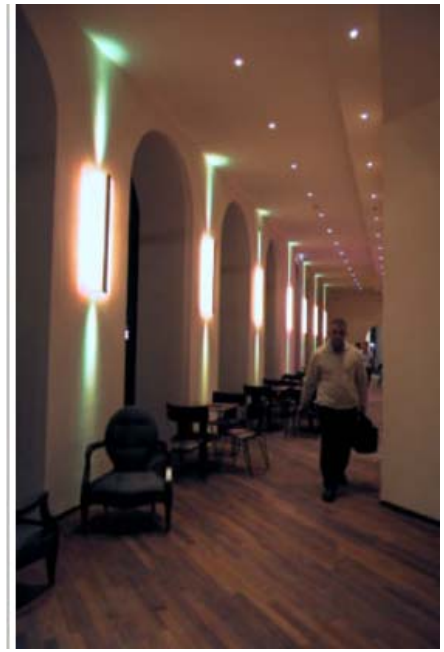
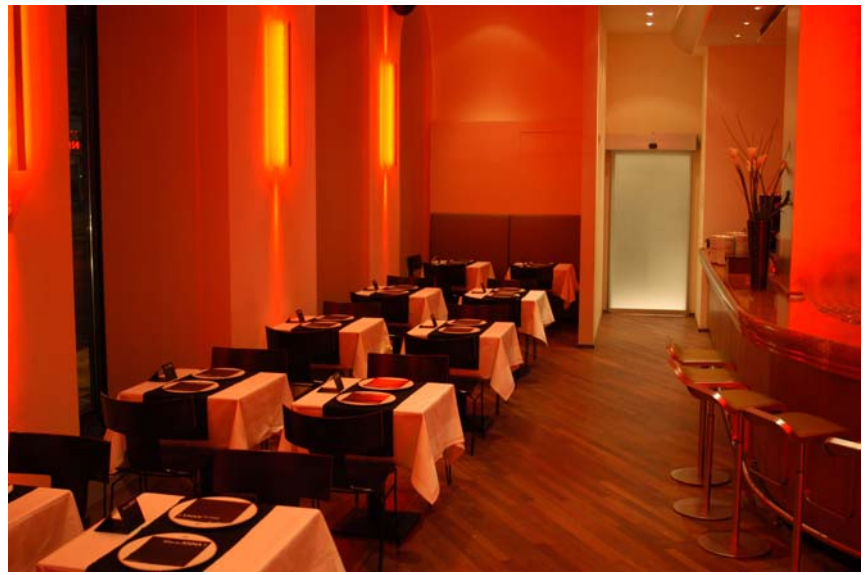
Restaurant Lighting





Hotel Anna in Munich

- **Style – Small size**
- **Dynamics white point and color control**
- **Dimming**
- **Energy Saving Directed Light**
- **Long Life, Reduced Maintenance**

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City Focal Point

Whiteleys Shopping Centre
Bayswater – UK
Installed Nov. 2002
Using 2000 RGB Luxeon

-Dynamic light
-Lower cost of ownership
-Reliability

City Focal Point

Glasgow / Scotland
White HB-LED lights railing
VP - Reliability, Maintenance, Energy

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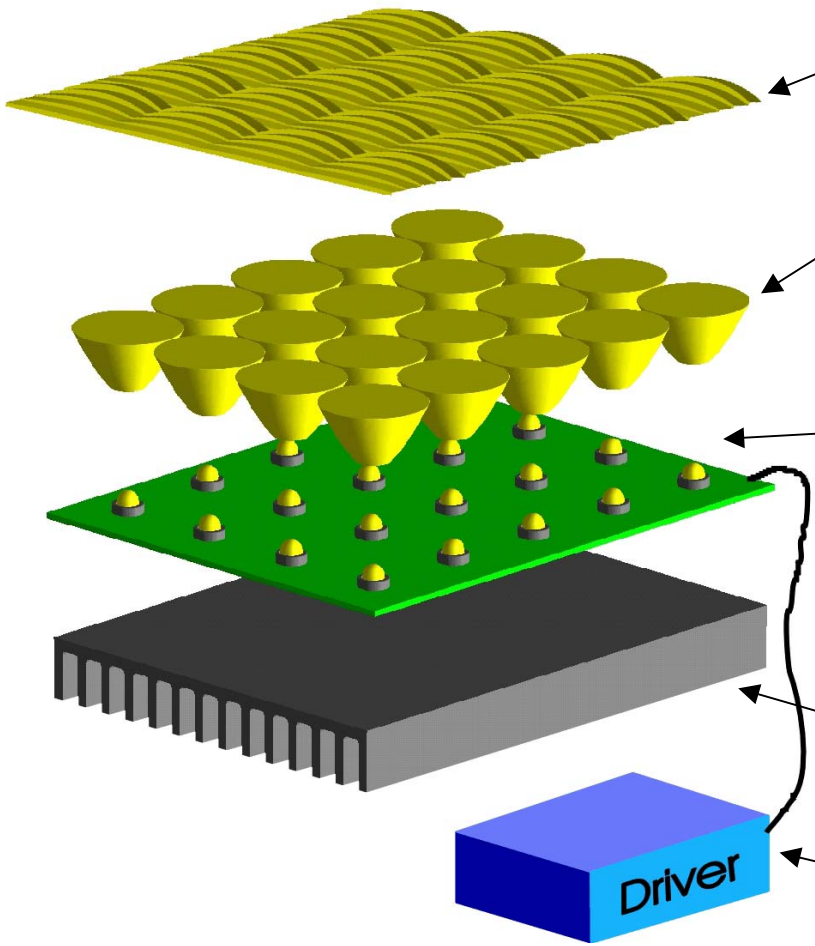
Presentation Agenda

- Introduction
- Technology
- Solid State White Light
- Luminaires and Applications
- Integration

Will LEDs work for me?

- Questions you Need to Ask
- A Model for Moving Forward

System Approach



Tertiary optics
Plastic tertiary optics can be designed to provide any desired light distribution pattern

Collimators
Injection molded plastic collimators maximize light collection from LEDs (over 90% optical efficiency) and offer a wide choice of beam widths.

Clustered LED arrays
Clustered high brightness LED modules assembled onto a metal core printed circuit board. Reliable connections provide mechanical sturdiness and good electrical and thermal conductivity.

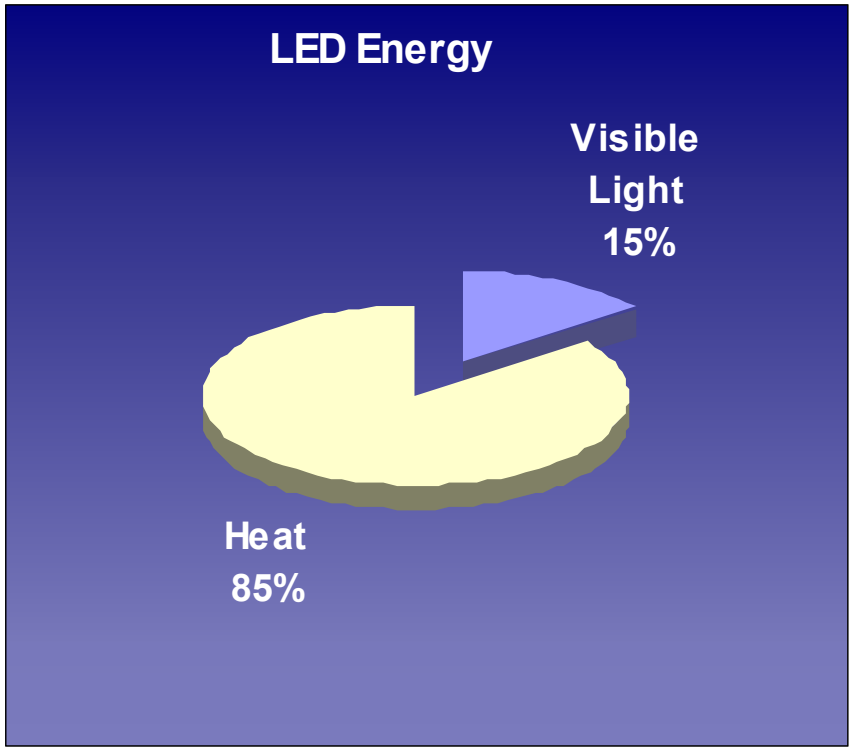
Heat sink
Heat management for optimal system efficiency

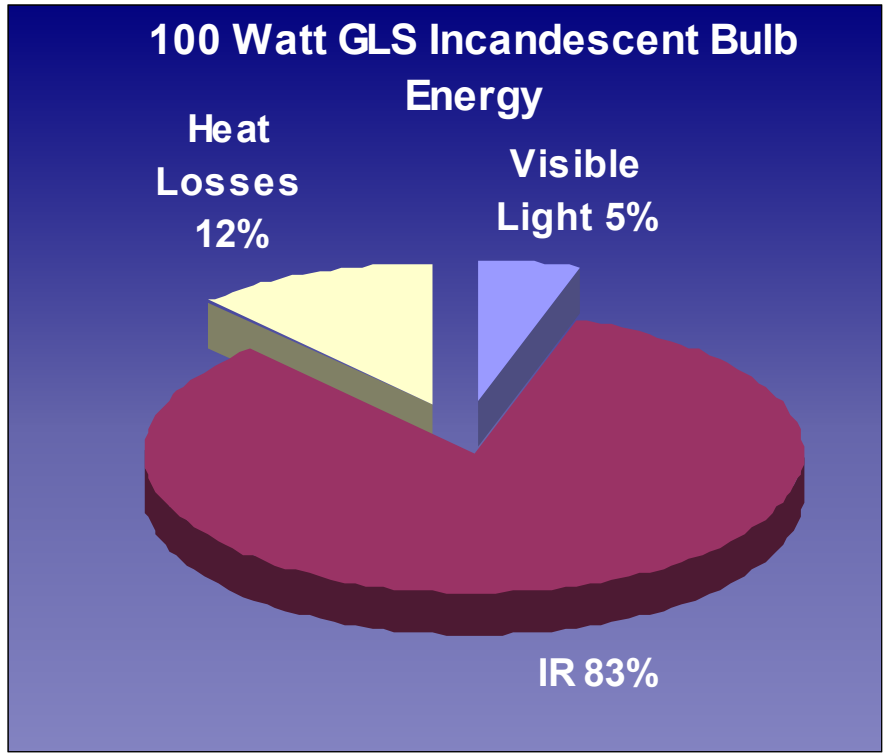
Driver
DC current power supply with any control functionality possibilities

Questions You Need to Ask

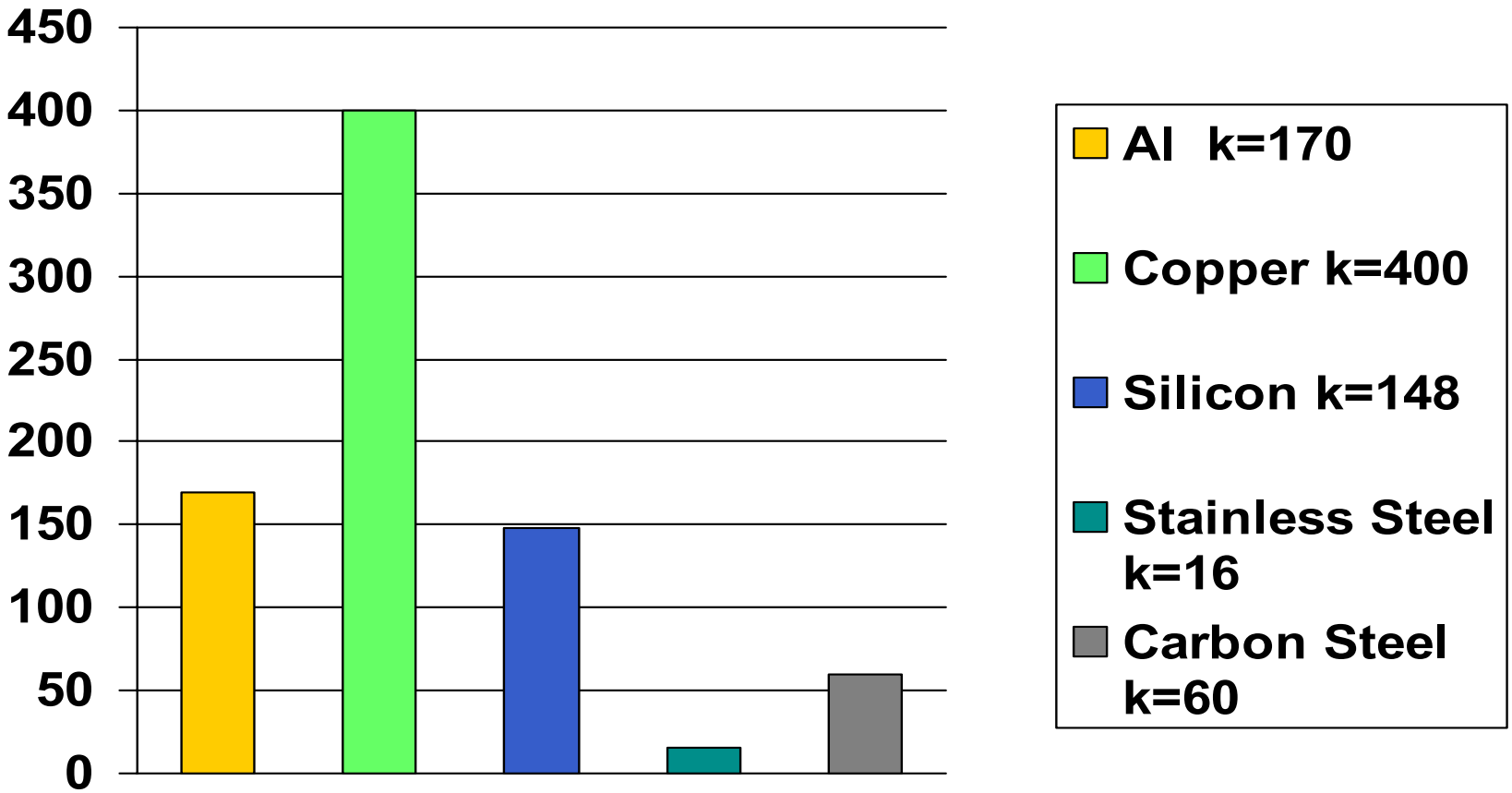
- Is the luminaire cooled properly?
- Are the LEDs powered/dimmed correctly?
- Will this create the lighting effect I want?
- Have you ensured color consistency?
- What will the lumen depreciation be?
- Does Led color rendering meet application needs?
- What is the overall system efficiency?
- How are optics affecting system efficacy?

Is it Cooled Properly?

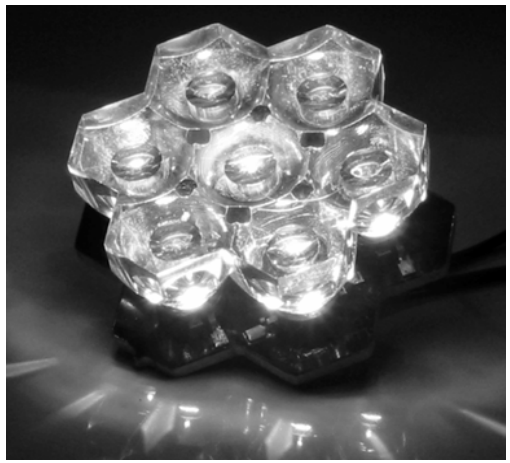




Is it Cooled Properly?
Examples of Thermal Conductivity



What can you do to minimize color variation?



- Can use multiple flux / colour bins
- Repeatable in volume applications
- Consider distance to illuminated object

- Can use multiple flux / colour bins
- Careful attention to mixing and optics

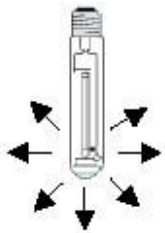
Courtesy Lumidrives

How are optics affecting system efficiency?

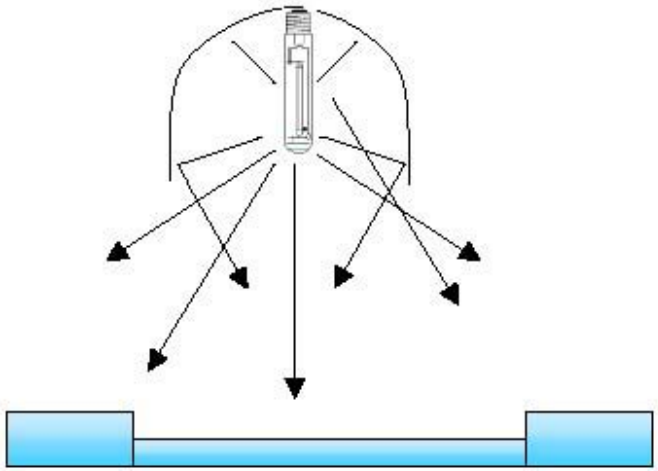
- Sputtered Aluminum reflector 80 to 85% efficient – also foils
- Plastic Lens 8% Fresnel loss
- Lens Optics emit in narrow angles
- Reflector optics emit in wider angles
- Encapsulating lens very efficient but big
- Micro optics

System Efficiency

HID:
100 lm/W



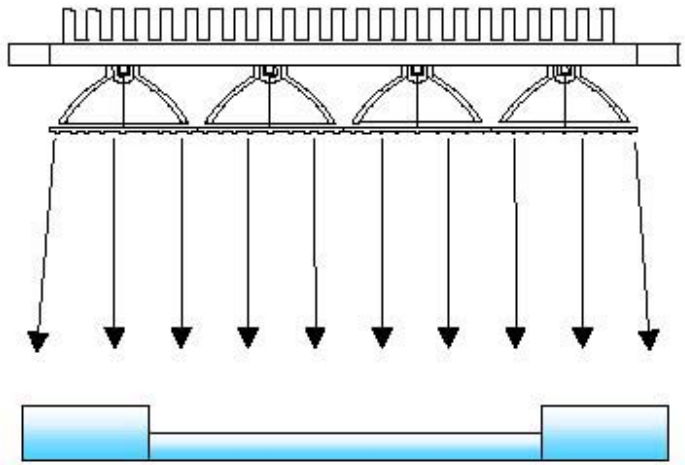
40% Utilization Efficiency



Lighting efficiency 40 lm/W

Amber LED:
50 lm/W

80% Utilization Efficiency



Lighting efficiency 40 lm/W

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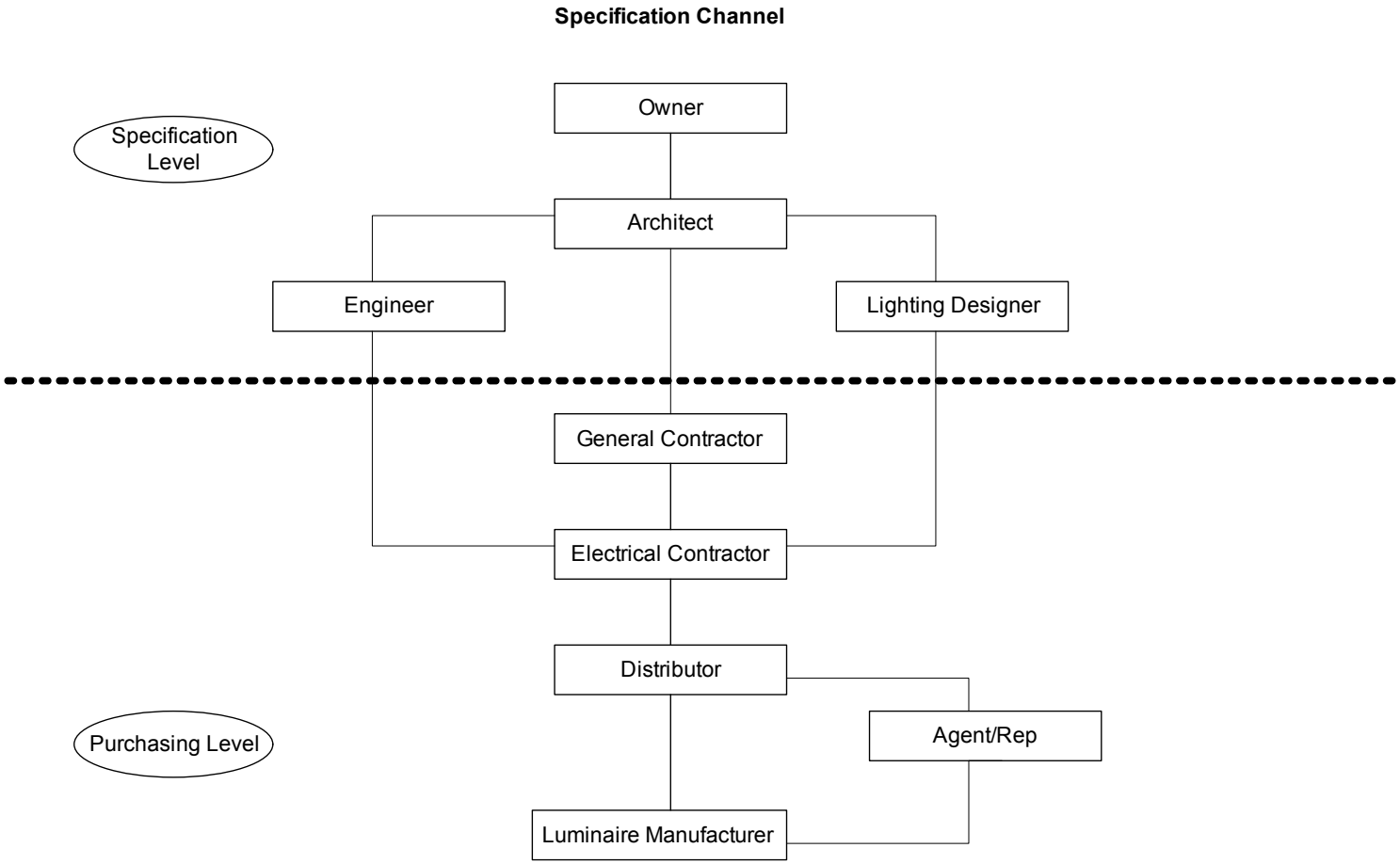
Lighting Community



Courtesy TIR Systems

Feedback from Designer/OEM Focus Groups

- Provide Value Propositions to:
  - End-User, OEMs, Solution Providers, LED Manufacturer
- Provide “Clean” Lighting Solution:
  - Uniformity of White
    - Optically
    - Binning refinement of Vf, Color/Tint and Flux continue with manufacturers
    - High Lumen and “color” maintenance
  - Warm White, High CRI for high quality lighting
  - High Lumen and LPW Packages
- Develop of a Solution Providers Network
  - thermal, optical, power supplies and control systems development
  - System integration
  - Color & white mixing routines being developed by solution providers

Industry Obligations to Specifier

- **Clarify opportunities and limitations of current technology**
- **Initial and long term system performance predictability**
- **Minimize system sizes and costs; develop ROI**
- **Meet the needs of the Luminaire manufacturer**
  - Via Solution Provider Network
  - Standards
- **Education**
  - About the technology
  - Delivery of system design and integration
  - Train OEMs and rep agencies
  - Simple “cut-sheets” for systems

Vision

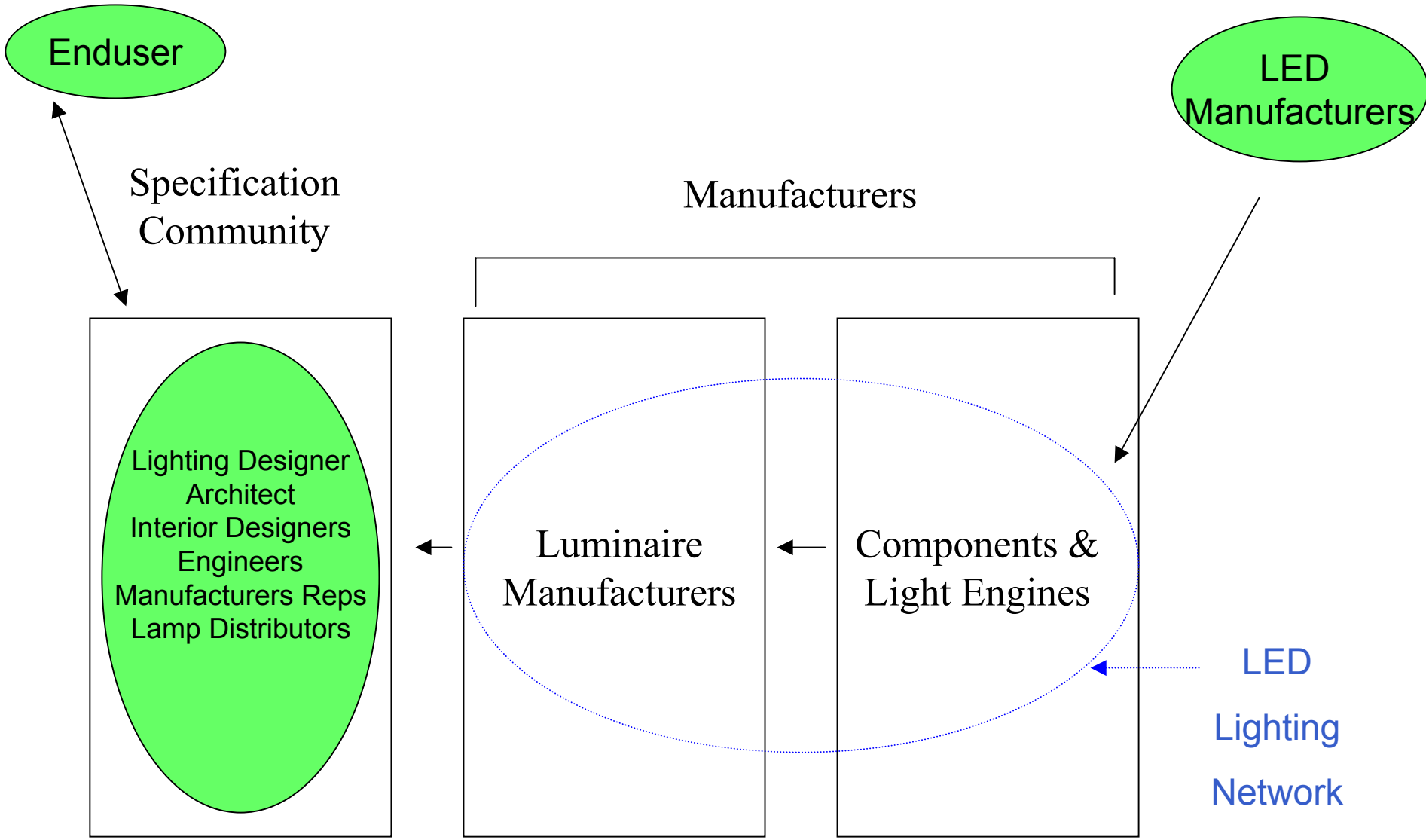
- **Enable a network of *System Providers***

  Each member has the capability and resources to design, develop, manufacture and guarantee the performance of a Luxeon based lighting system from concept through installation.

- **Enable a network of *Luminaire OEMs***

  Each member has the capabilities and resources to design, develop and manufacture Luxeon based luminaires with a performance guarantee

LED Lighting Network



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Lighting Industry Benefits

- **Instill confidence in specifiers and end-users in High Power LED-based system-solutions**
- **Provide manufacturers “de-facto” design/development standards**
- **Accelerate market pull for development and adoption of SSL systems**
- **Resolve “white” tint challenge – by design and in coordination with industry**

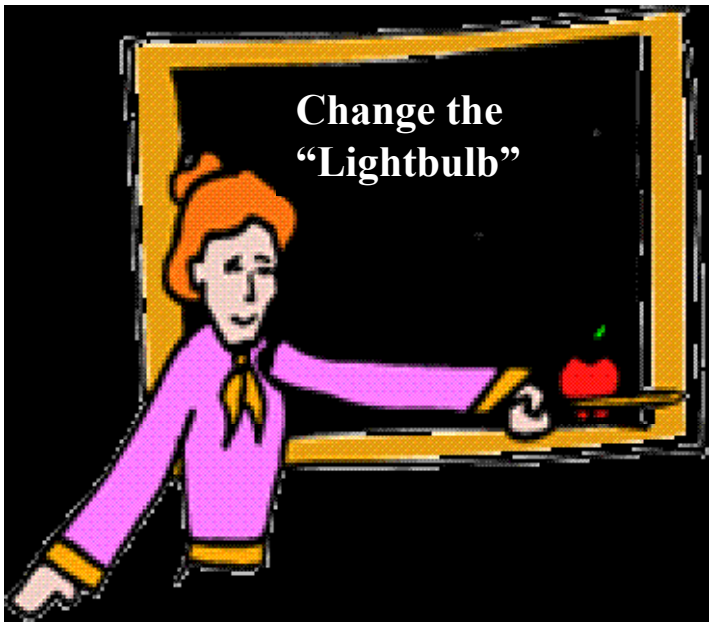
We believe that if we do this…

We Provide Lighting Designers and OEMs:

- **Ability to design products Never Before Possible**
- **Ability to offer products with better energy efficiency, environmental soundness, and intelligence WHILE improving design creativity.**
- **New products for new markets, competitive differentiation**

Illumination in the Future

Fast forward: 25 years



What's a lightbulb and why would anyone want to change one?

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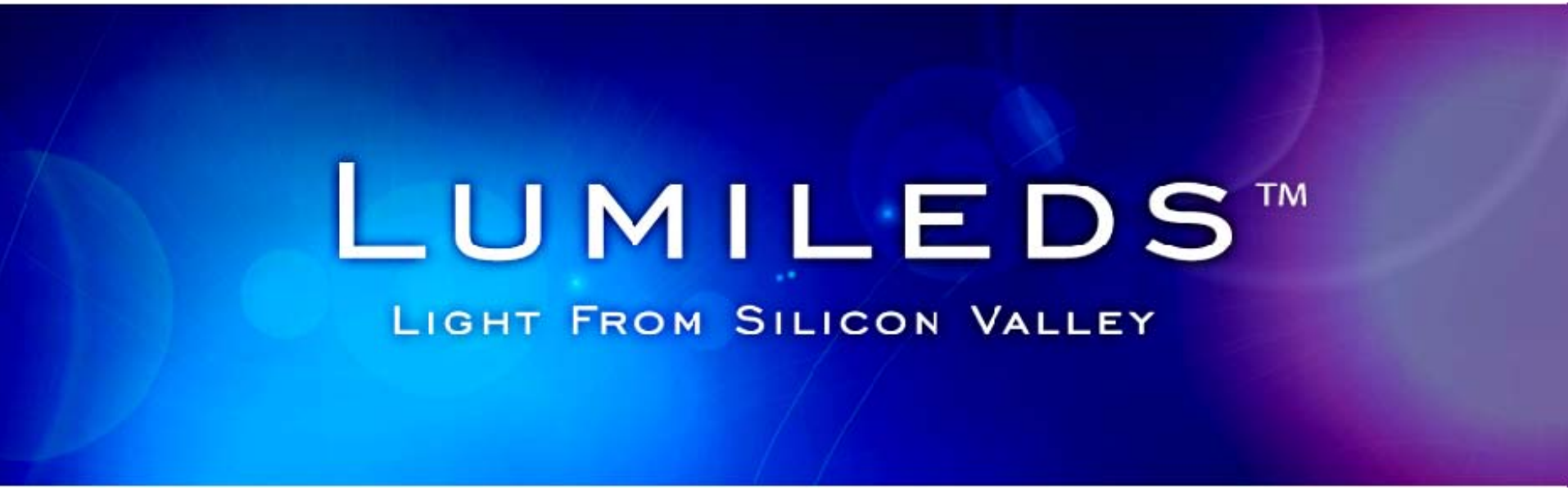

Thank You