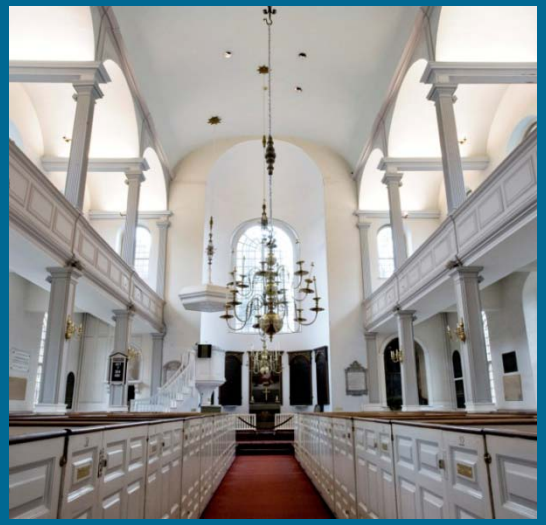
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

LED Basics: Technology Fundamentals for Novices



2010 DOE SSL Market Introduction Workshop

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Tutorial

Format

- 20 minutes presentation
- 10 minutes Q & A

Objectives

- 18 key fundamentals
- Separate fact from fiction
- Navigate marketing
- Identify what you need to learn more about

Later Today

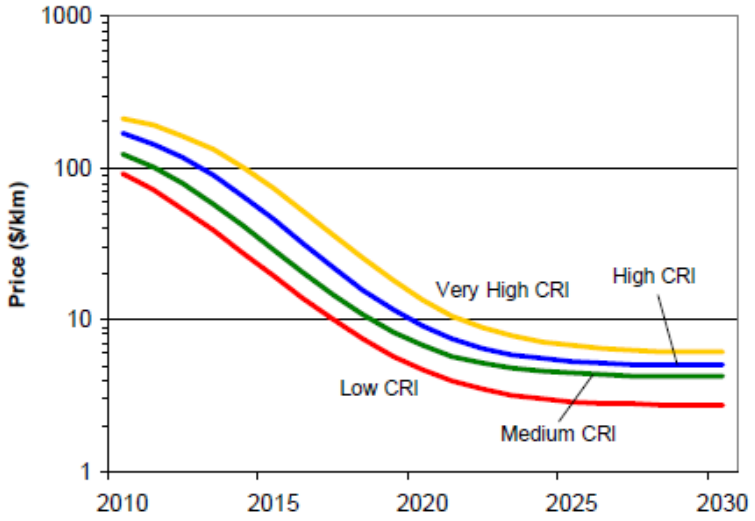
- Lighting Performance
- Standards (LM-79, LM-80)
- Products (CALiPER)
- DOE Lighting Facts
- Applications (GATEWAY)

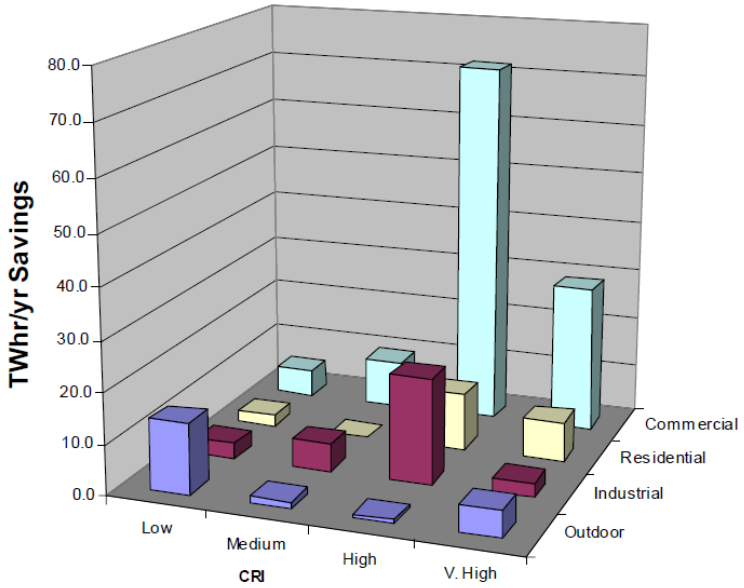
18 Key Fundamentals

1) Value Proposition
2) Physics
3) Photons
4) Heat
5) Voltage, Current & Time
6) White Light
7) Directionality
8) Lumen Maintenance
9) Thermal Management
10) System
11) Packages
12) Power Control
13) Dimming
14) Efficiency
15) Efficacy
16) Lifetime
17) Cost
18) Learning Curve

1) Value Proposition

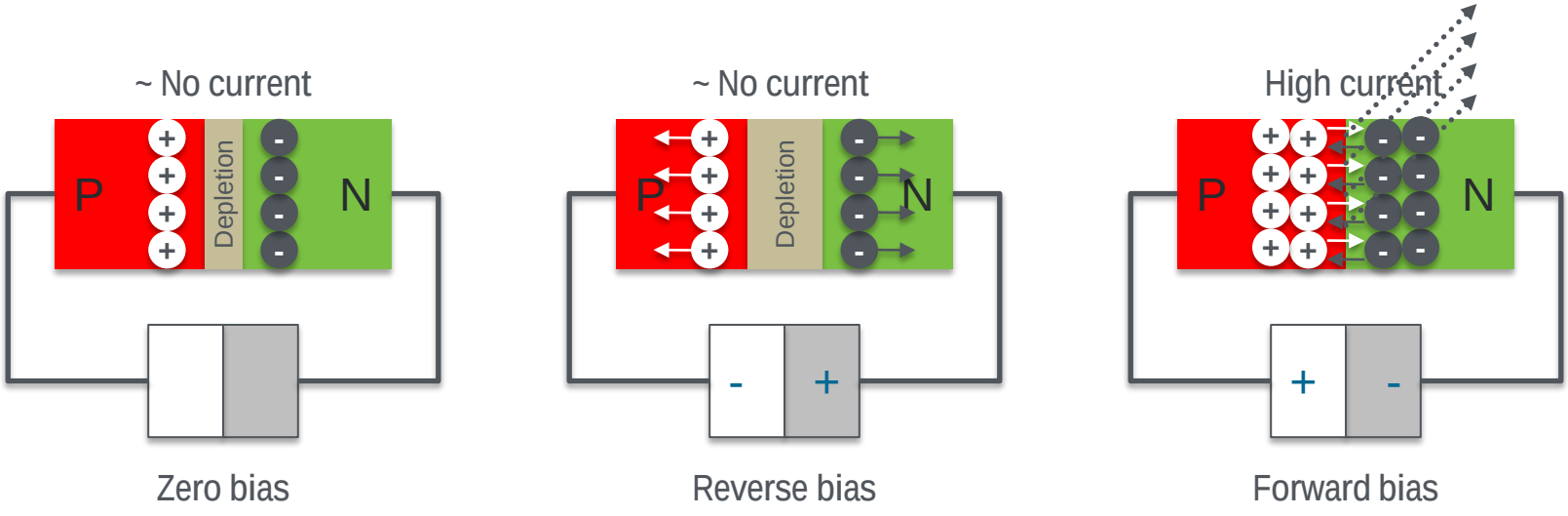
- Potential to save energy
  - Over 2010-2030: 1488 terawatt-hours
  - By 2030: 190 terawatt-hours/year (25% reduction)
- Potential to save (you?) money
  - Over 2010-2030: $120B ($today)
  - By 2030: $15B ($today)
  - Factor in install cost, maintenance cost, achieved lifetime
  - Individual results will vary





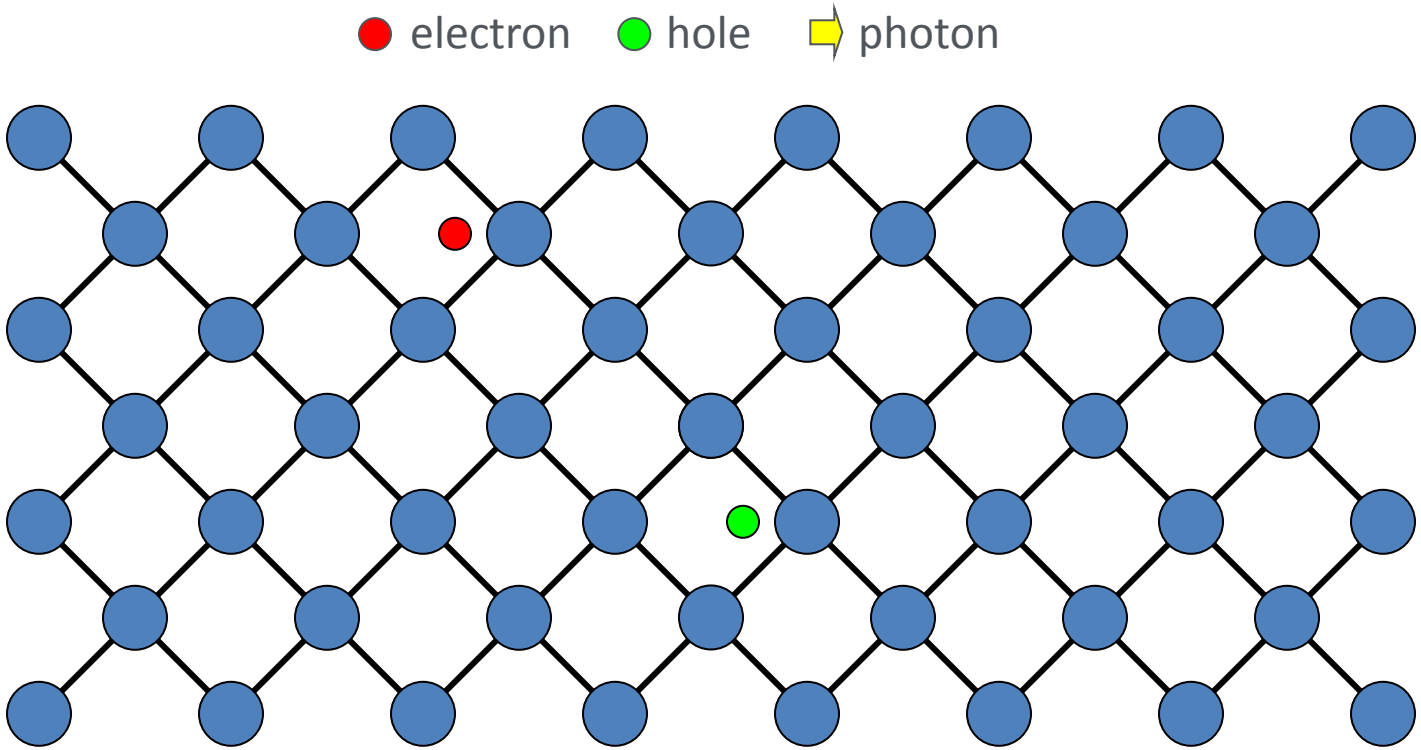
2) Physics

- LEDs are polar semiconductor devices formed by the creation of a P-N junction
- Current only flows in one direction, under forward bias and the collapse of the depletion region
- Narrowband light is generated in the P-N junction as a result of current flow under forward bias
- The wavelength of the light generated depends on the band gap energy of the materials forming the P-N junction.



3) Photons

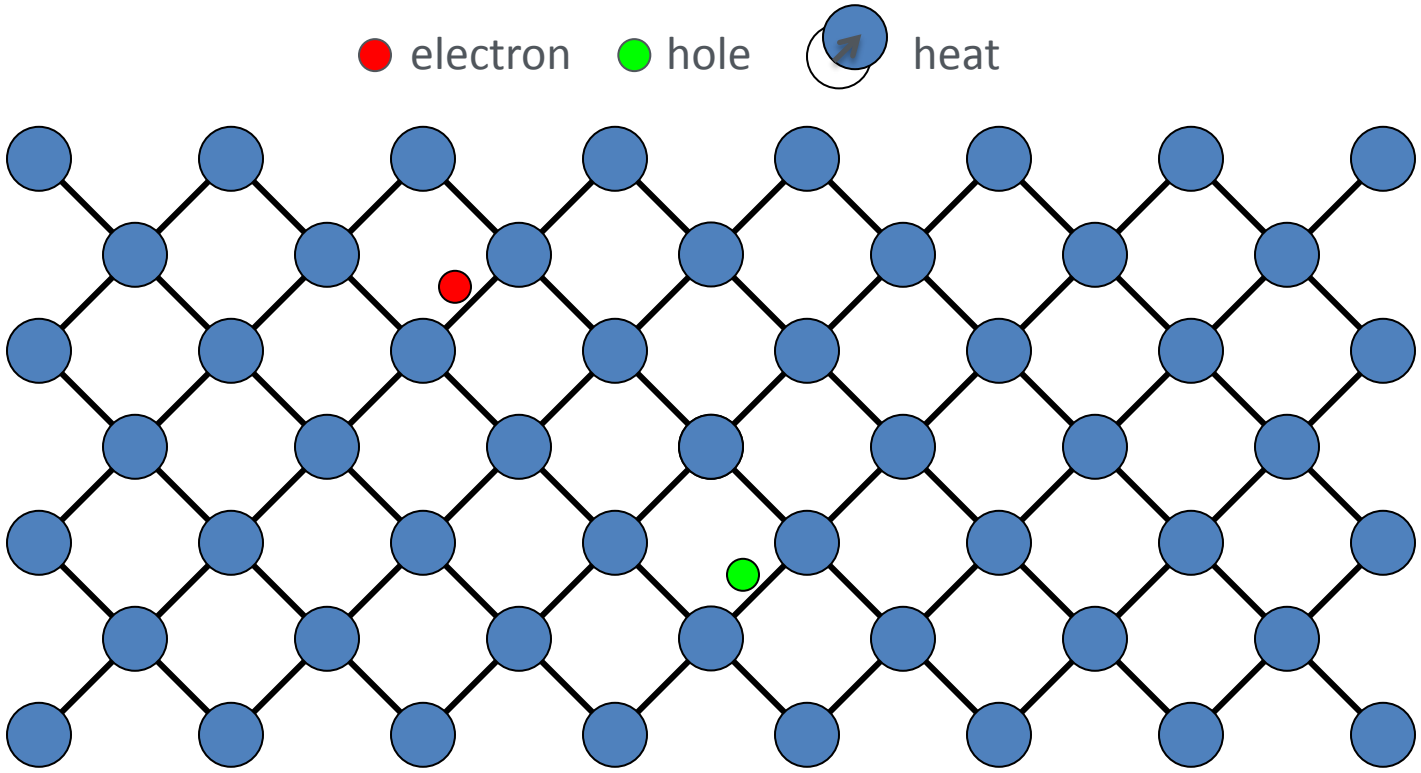
- Photons are generated by electroluminescence (electric current), as opposed to incandescence (heat).
- Electroluminescence is the result of radiative recombination of electrons and holes in a semiconductor.



Source: LED Transformations

4) Heat

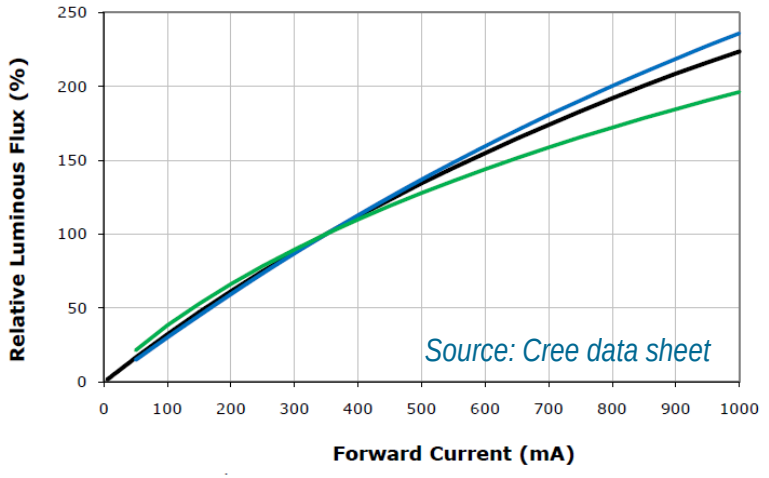
- Recombination of electrons and holes does not always result in electroluminescence
- Heat is the result of non-radiative recombination of electrons and holes in a semiconductor.

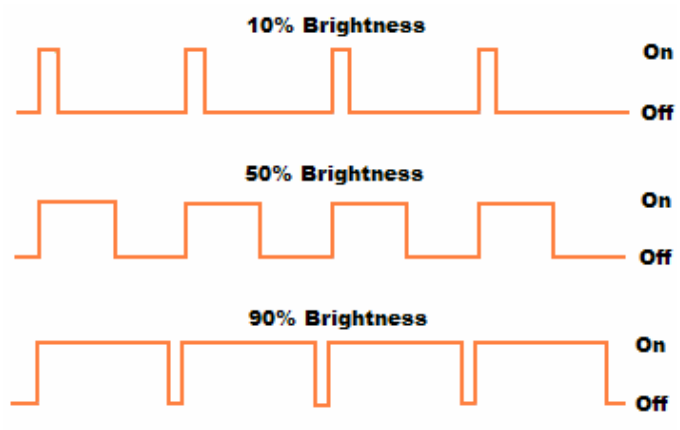


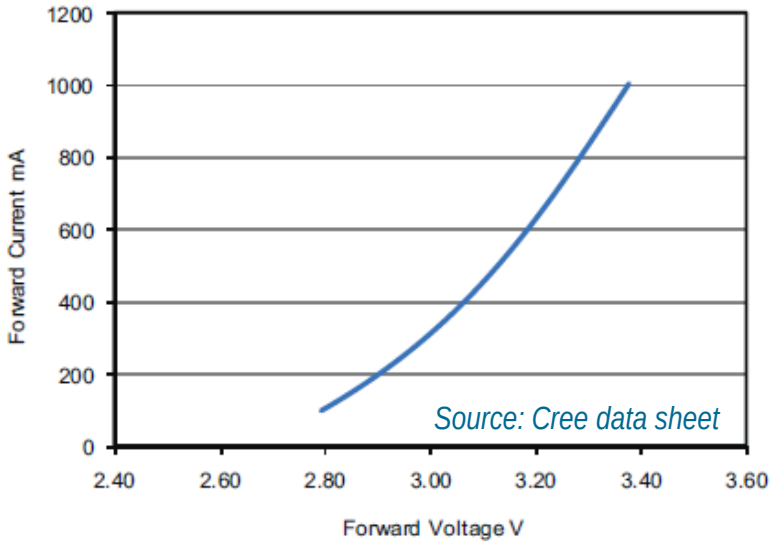
Source: LED Transformations

5) Voltage, Current, & Time

- Luminous flux increases with LED current (I_F)
- LED current is a non-linear function of forward voltage (V_F)
- LED response time is very fast
  - Allows for PWM dimming
  - Improves potential for control (e.g. occupancy sensing)
  - Can result in undesirable flicker

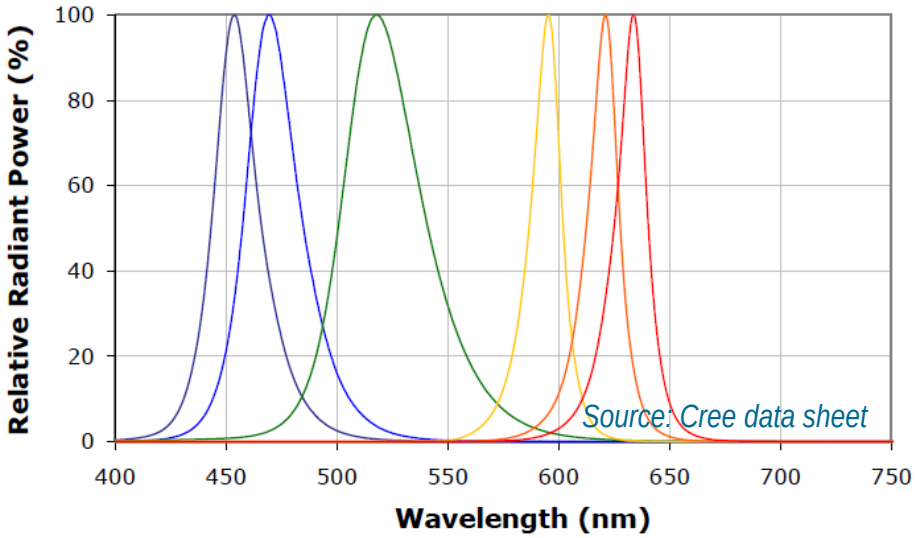


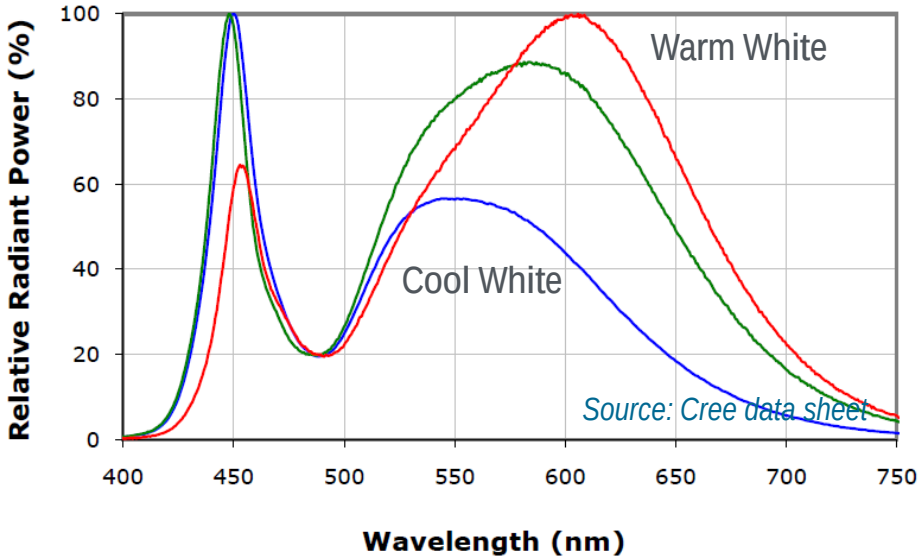




6) White Light

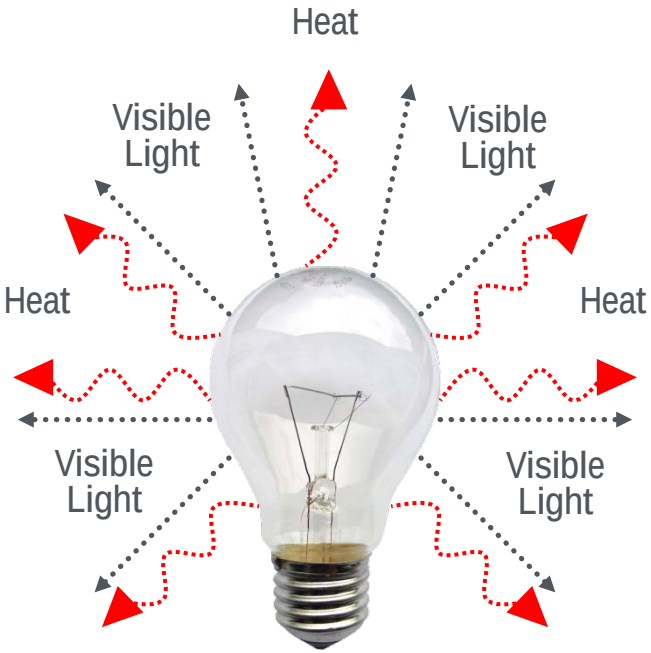
- LEDs are narrowband light sources
- Many techniques for making white light
- Most common
  - Blue LED + Yellow Phosphor = Cool White
  - Blue LED + Yellow Phosphor + Other Phosphor = Warm White
- Less common
  - Red LED + Green LED + Blue LED
  - UV LED + R-G-B Phosphor(s)
  - Blue LED + Yellow Phosphor + Red LED
- Phosphors
  - Downconvert short wavelength (higher energy) to longer wavelength (lower energy)
  - Efficiency (Stokes loss)
  - Performance degradation over time/temperature



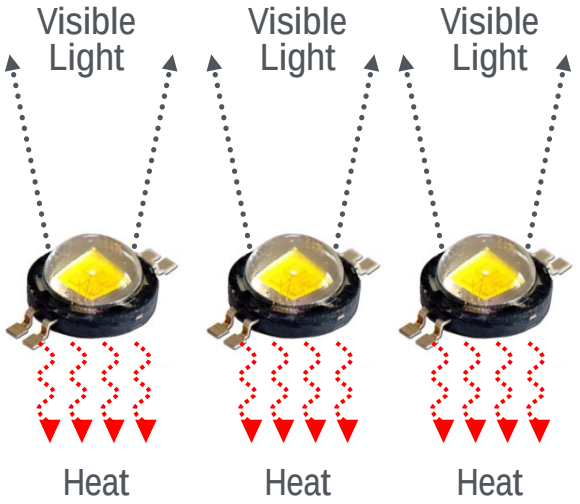


7) Directionality

- Omni-directional light
- Generated heat radiated away (IR)

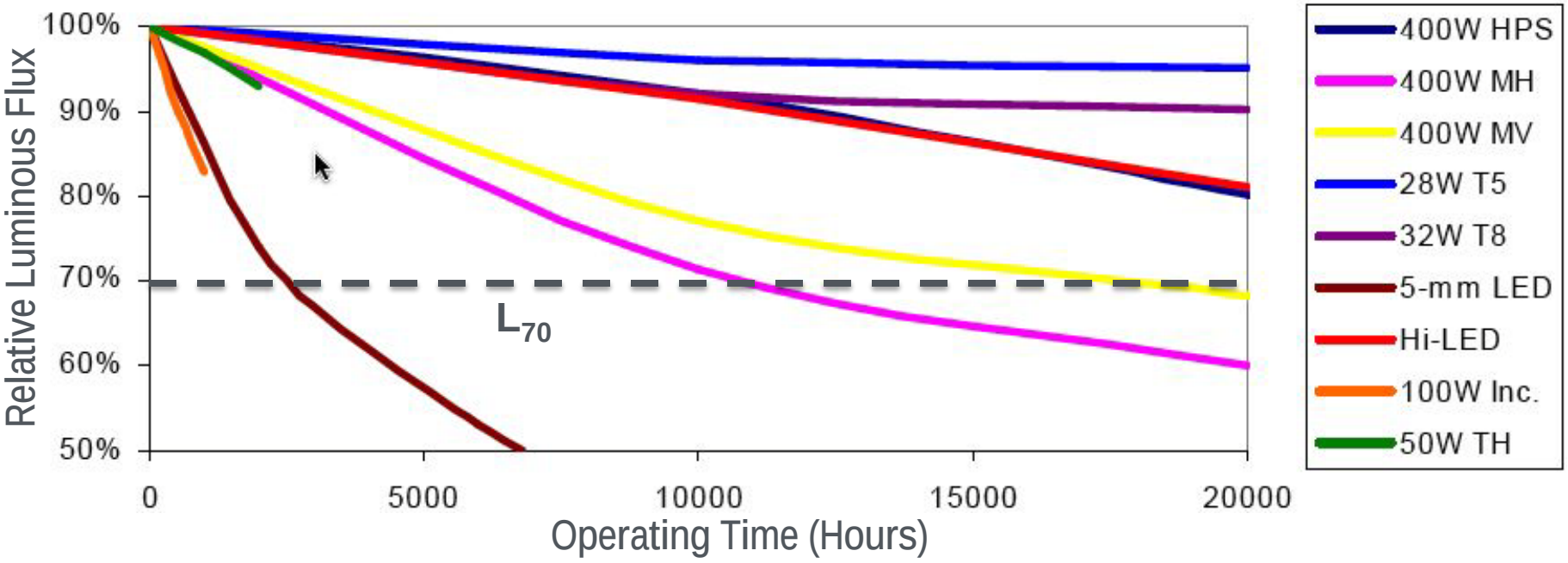


- Directional light
  - Index of refraction change
  - Internal reflector
- Generated heat transferred by conduction (primary) and convection



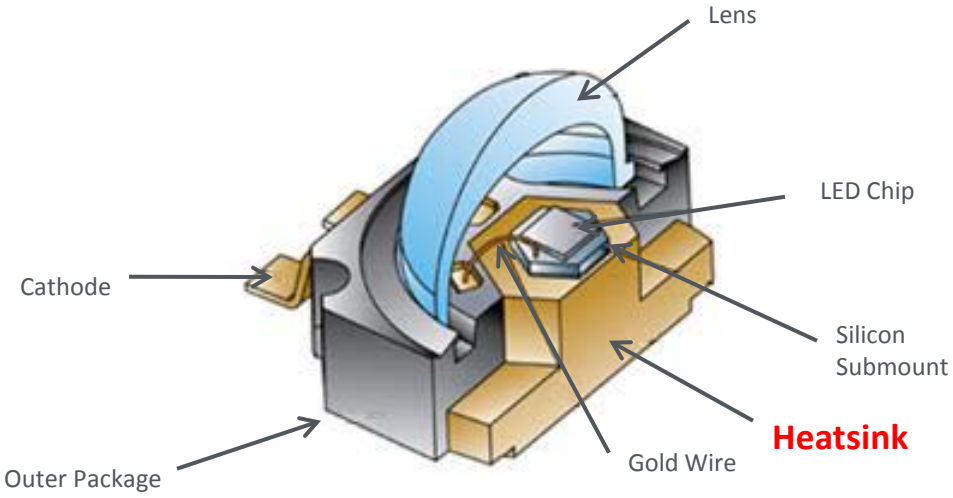
8) Lumen Maintenance

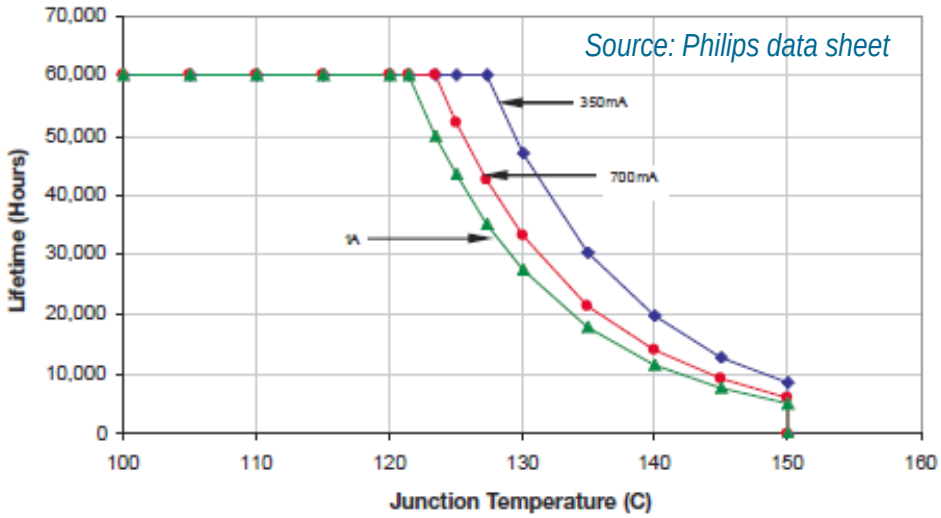
- The output of all light sources degrades over time.
- Source end of life
  - Catastrophic failure
  - Or 30% reduction (70% maintained) in light output (L_{70})
  - IESNA: A change of about 1/3 is just perceptible
- It has been difficult to predict the long term lumen maintenance of LEDs with only limited lifetime data



9) Thermal Management

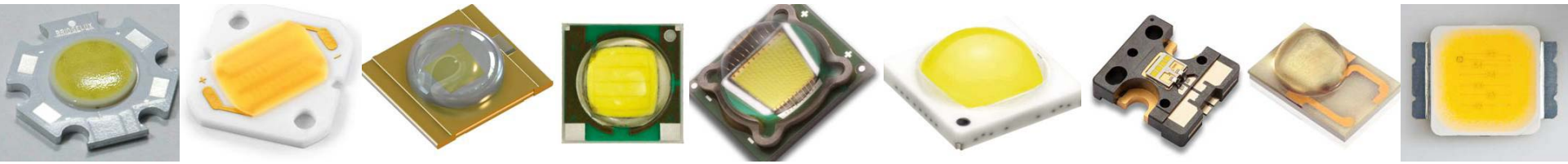
- The key to long LED lifetime
- Operation at higher junction temperatures Tj results in lower lifetime
- Tj must be managed in system design
  - Ambient temperature
  - Thermal path between the LED junction and ambient
  - LED power
- The package heatsink provides a (low) thermal resistance pathway





10) Packages

- Electrical interface
- Thermal interface
- Mechanical support/protection
- Primary optic(s)
  - Lens
  - Internal reflector
- Die
  - Size
  - Maximum current/power
- Lens
  - Material (silicone)
  - Beam spread
- Phosphor
  - Type
  - Deposition technique
  - Performance
  - Lifetime



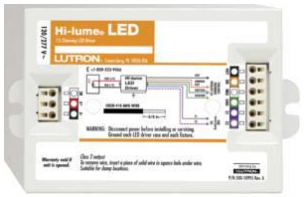
11) System

- An LED luminaire is a system
- Every component in the system not only adds function (and cost), but often affects the performance of the other components, and can be a factor in determining lifetime

50/60 Hz

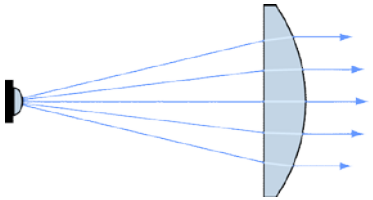
Dimmer

Power Control

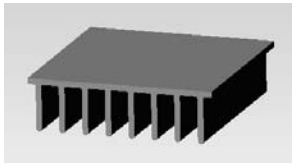


Package

Secondary Optics



Diffuser



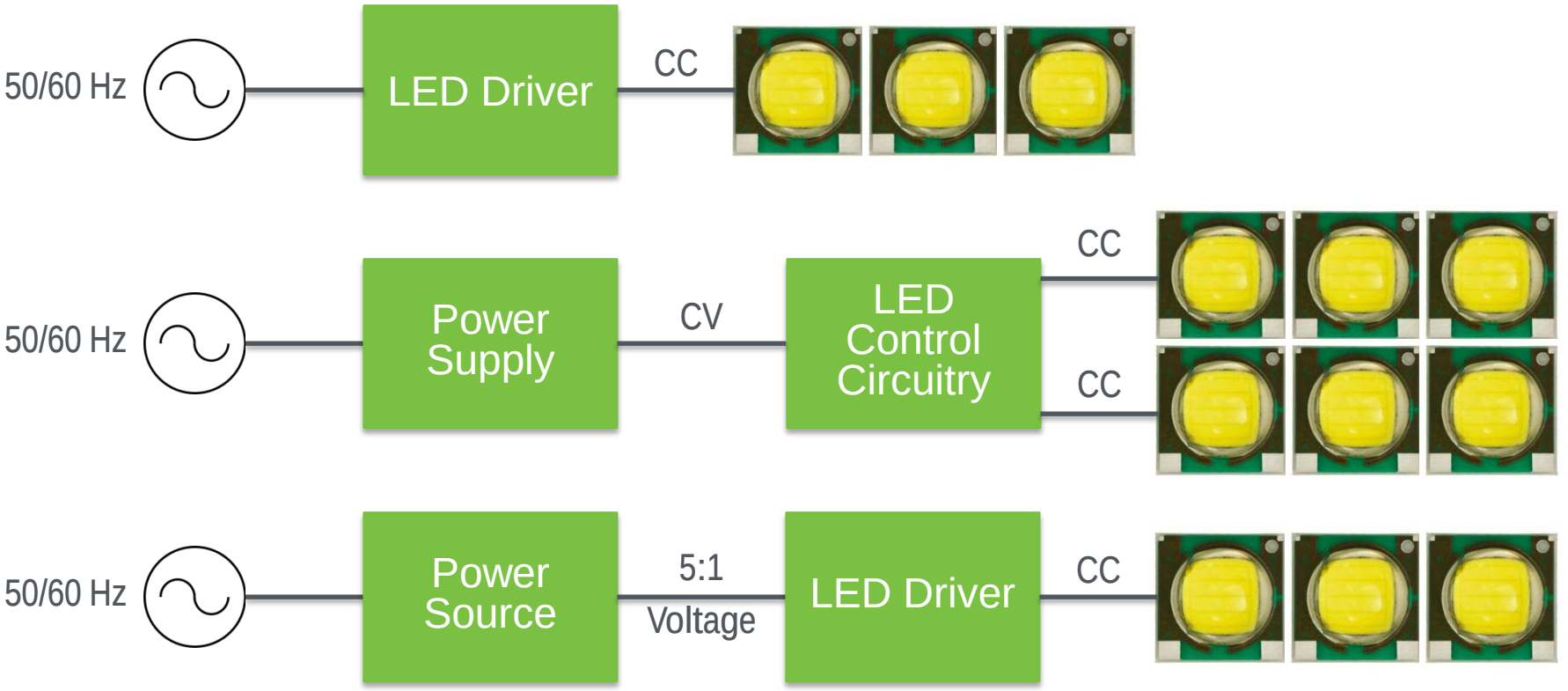
Secondary Heat Sink

12) Power Control

Terminology (IES RP-16 addendum B)

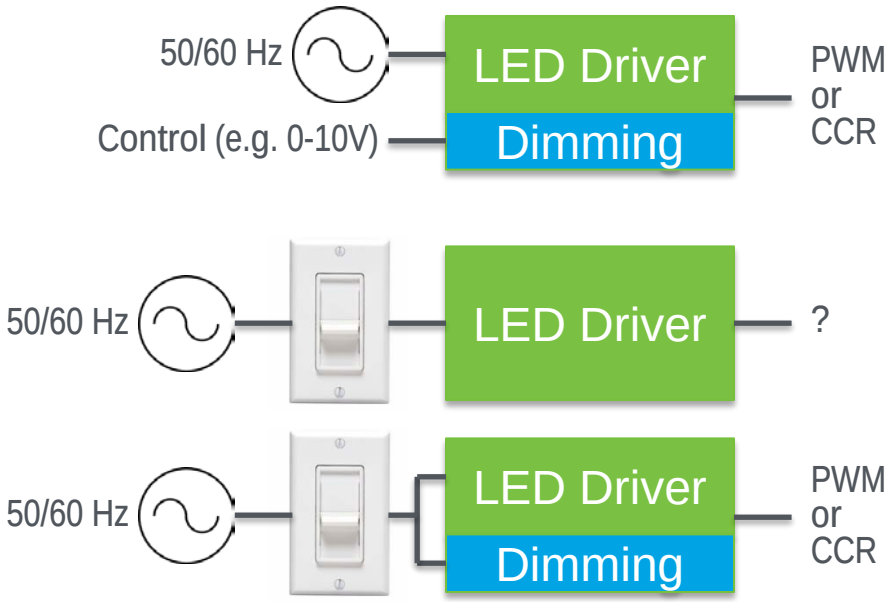
- Power source
  - A transformer, power supply, battery, or other device capable of providing current, voltage, or power within its design limits. This device contains no additional control capabilities.
- Power supply
  - An electronic device capable of providing and controlling current, voltage, or power within design limits.
- LED control circuitry
  - Electronic components designed to control a power source by adjusting output voltage, current or duty cycle to switch or otherwise control the amount and characteristics of the electrical energy delivered to a LED package (component) or an LED array (module). LED control circuitry does not include a power source.
- LED driver
  - A device comprised of a power source and LED control circuitry designed to operate a LED package (component), or an LED array (module)or an LED lamp.
- http://ies.org/PDF/Erratas/RP_16_05addendumB.pdf

12) Power Control (examples)



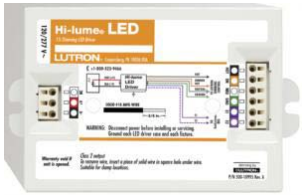
13) Dimming

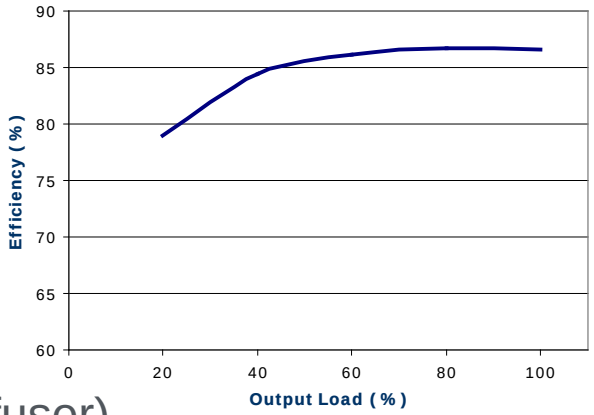
- LEDs ARE capable of high performance dimming
  - Dimming control, power control compatibility is key
  - Some dimmer manufacturers do compatibility testing with some products
- Integral (to LED Driver)
  - Needs control signal
  - Pulse Width Modulation (PWM)
    - Frequency
    - Dimming range
    - Potentially undesirable flicker
  - Constant Current Reduction (CCR)
    - Color shift
- Line voltage
  - Performance highly dependent on interaction with LED driver
  - Some LED drivers read phase and translate to PWM or CCR
  - Phase chopping
    - Efficiency
    - Harmonics
    - Potentially undesirable flicker
- NEMA committee working on improving compatibility
  - Best practices (today)
  - Potential standard (future)
  - http://www.nema.org/stds/lsd49.cfm



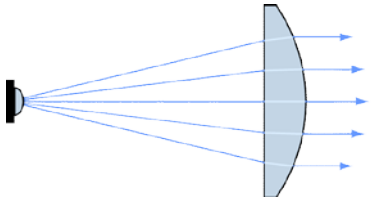
14) Efficiency

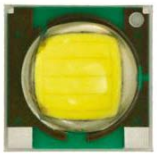
- Efficiency (%) = Desired Output / Input
  - Electrical (Power Control)
  - Not constant: load dependence





  - Optical (Lumen Control: Secondary Optics, Diffuser)

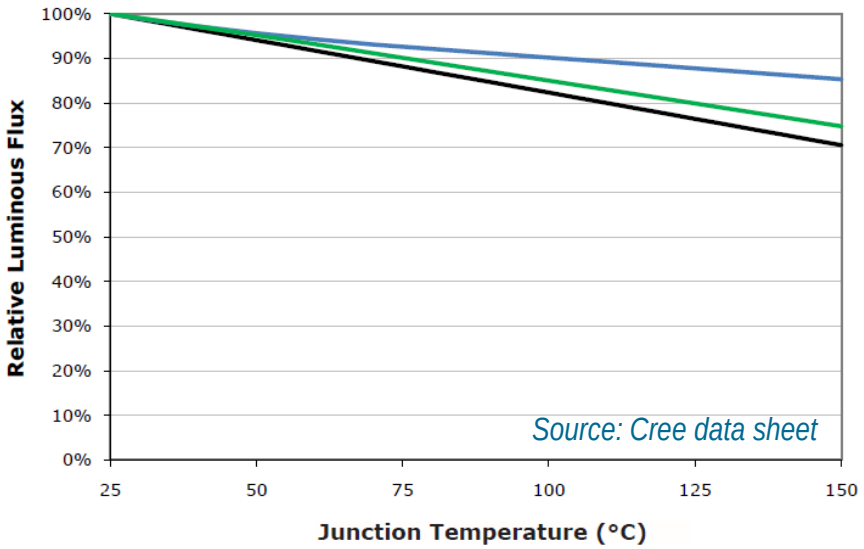




POWER IN → x Power Factor? x Electrical Efficiency → x Optical Efficiency → LUMENS OUT

15) Efficacy

- LED efficacy ≠ constant
  - Drops at higher currents
  - Drops at higher junction temperatures
- LED efficacy (lm/W) = $\frac{\text{luminous flux } (I_F, T_j)}{I_F \times V_F (I_F)}$
- System efficacy ≠ LED efficacy
- System efficacy (lm/W) = LED efficacy (lm/W) x Electrical Efficiency (%) x Optical Efficiency (%)

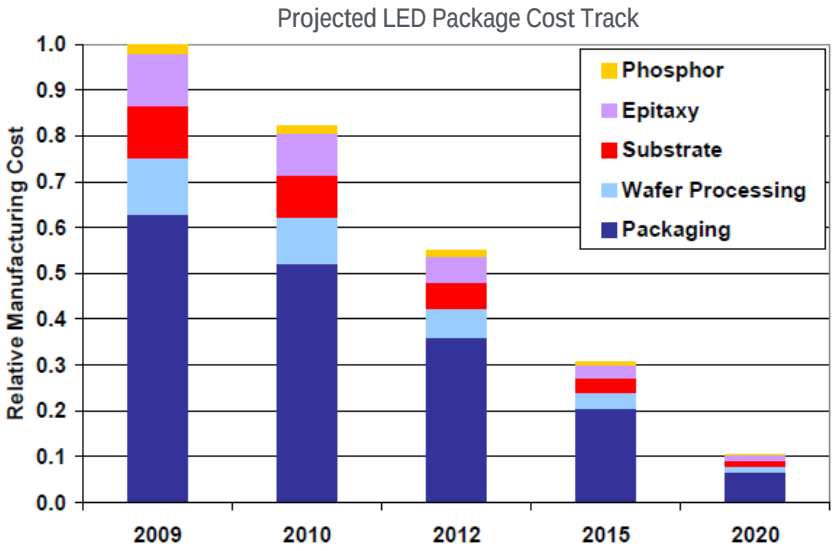


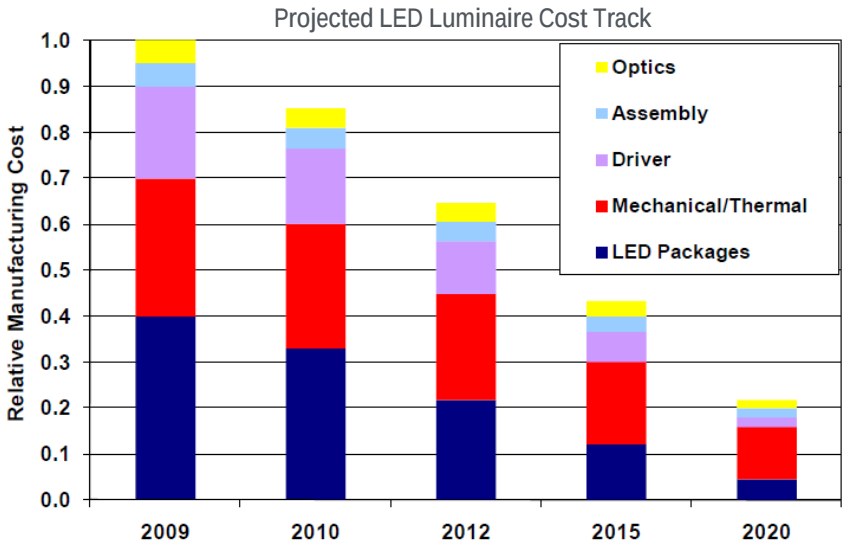
16) Lifetime

- LED lifetime ≠ constant
  - Drive current and junction temperature
- System lifetime ≠ LED lifetime
  - Lumen Maintenance (L_{70}): array of LEDs, Optical, Thermal
  - Catastrophic Failure: Electrical, Mechanical, Connections, some LEDs?
- Lifetime
  - Statistical metric
  - Statistical significance? Mean? Median? B_{yy}?
    - B_{50} = median = traditional source “rated life”
  - How is it calculated?
    - NO STANDARD TODAY
    - Not LM-80; maybe TM-21
  - Predicted (component models?) or measured (acceleration factors)?
- Warranty
  - Conditional metric
  - What is covered?
  - Ability to stand behind it?

17) Cost

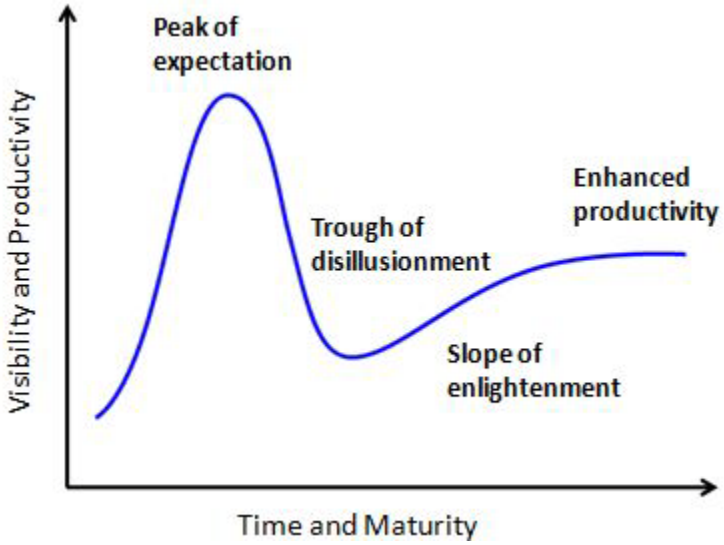
- High but coming down steadily
- Maintenance is still a necessary part of the equation
- Long life introduces new application-specific considerations
  - Cleaning
  - Increased transient event exposure (e.g. surge)





18) Evolving learning curve

- Disruptive technology
- Innovation ongoing in all system component areas
- Beware of generalizations, marketing hype
- Get Smart. Ask questions. Validate information.



Using LEDs, Fact Sheets

- ssl.energy.gov/using_leds.html
- ssl.energy.gov/factsheets.html
- Basics, Applications, Measurements, Performance specification
- Ongoing updates

Technical Reports

- Program Plan: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2010_web.pdf
- Manufacturing Roadmap: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_manuf-roadmap_july2010.pdf
- Energy Savings: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_energy-savings-report_10-30.pdf

Conferences

- ssl.energy.gov/conferences.html
- Up next: R&D in February 2011