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Dimming LED sources: what's working and what still needs fixing

Michael Poplawski (Pacific Northwest National Lab)
Ethan Biery (Lutron Electronics)

Tuesday, May 7, 2012 9am-12noon

PRE-CONFERENCE
LIGHTFAIR Daylighting Institute®
LIGHTFAIR Institute®
Monday, May 7 –
Tuesday, May 8, 2012

TRADE SHOW & CONFERENCE
Wednesday, May 9 –
Friday, May 11, 2012

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Agenda

- Introduction (5 minutes)
- What's working: Dimming today's LEDs (10 minutes)
- Old vs. new world of dimming (50 minutes)

BREAK (15 minutes)

- What still needs fixing: The technical nitty-gritty (50 minutes)
- Recommended practices for dimming today's LEDs (15 minutes)
- Standards & Specifications update (15 minutes)
- Closing comments, followed by Q & A (20 minutes)

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Introduction

Why dimming is important

- Enhance space ambiance, flexibility
- Increased visual task performance, task tuning
- Save energy, daylighting
- Potentially fewer products to specify
  - Less value engineering (hopefully)
  - More sustainable commissioning (maybe)
- Potentially simpler, cheaper lighting system management
  - Reduced operating costs
  - Fewer user complaints (too bright or too dim)
  - Reduced maintenance cost (fewer products to stock)
- LED Bonus: potentially improved light source efficacy, lifetime
  - Only technology that has the potential to get more efficient as it is dimmed
  - Lower component (LED, phosphor, electronics), lamp, luminaire operating temperatures can lead to longer lifetime

Who cares about dimming

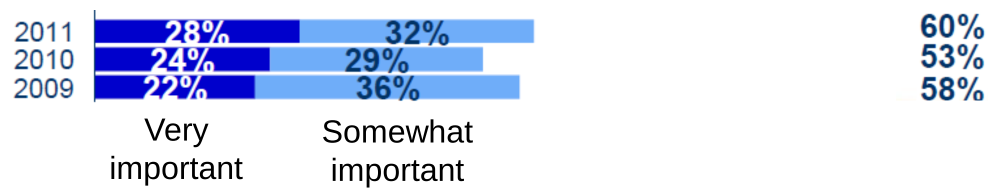
- Technology early adopters
  - Often looked to as opinion leaders
- General consumers
  - Early experiences hard to overcome (CFL lessons learned)
- Lighting designers
  - Satisfy owner, manager, occupants, codes and standards
- Facility and municipality managers
  - Occupancy, curfew, seasonal, safety, police/fire response
- Utility managers and energy-efficiency programs
  - Energy-efficiency, peak load shedding, demand response
- Codes and standards bodies

Sylvania Lighting Surveys

2011 Socket (Consumer) Survey

Q4. I'm going to read you a list of various properties of light bulbs some people consider when making purchasing decisions. Please tell me how important each of these is to you personally when you choose a light bulb.

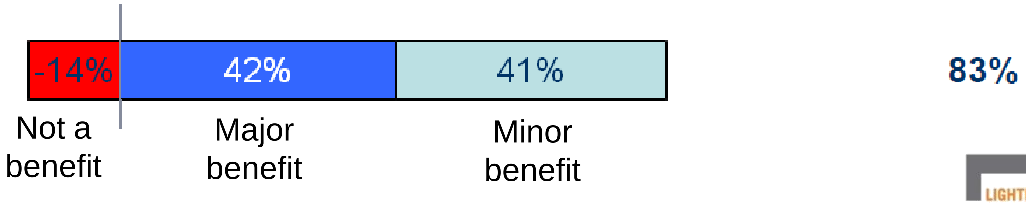
If the bulb can be dimmed, so you can control the brightness of light coming from the bulb



2010 Commercial Survey

Q35-42. I'm going to read you a list of potential benefits to using LED lighting that may be important to some companies and less important to others. Please tell me how important each one would be to [your company]/[your clients]. Would it be a major benefit, a minor benefit, or not a benefit at all.

That LEDs can be dimmed, directed and controlled more easily that other lighting options.



http://www.sylvania.com/en-us/tools-and-resources/surveys/Pages/socket-survey.aspx
http://www.sylvania.com/en-us/tools-and-resources/surveys/Pages/commercial-survey.aspx

Residential Energy Codes

- IECC – 2009
  - Requires that 50% of sources are high-efficacy
  - Does not have any control requirements
- California Title 24 - 2008
  - Offers dual compliance path for many rooms of the house
    - High-efficacy sources
    - Low-efficacy sources + vacancy sensor or dimming
  - Resulted in large installed base of dimmers connected to incandescent sources
- California Title 24 – 2014
  - No current proposal to add new dimming requirements
  - Laundry, Utility, Garage must be high efficacy AND vacancy sensor.

Commercial Energy Codes

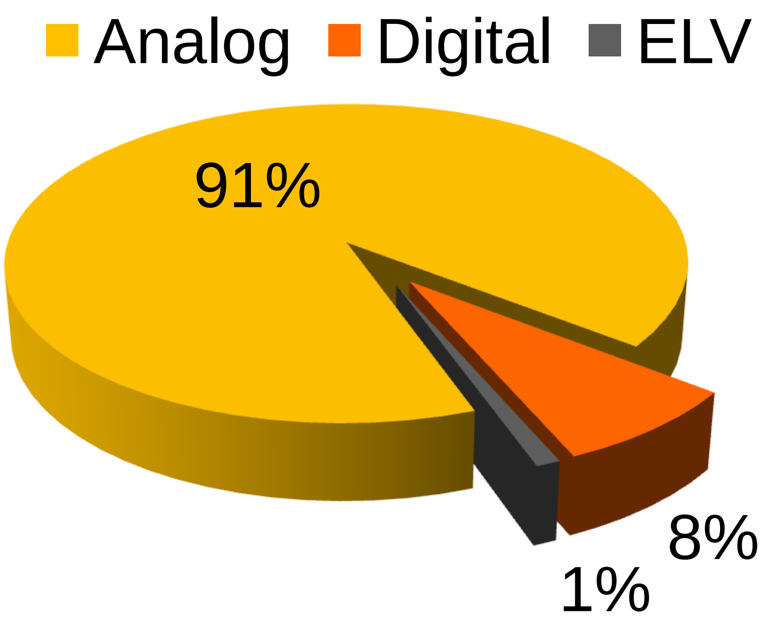
- IECC 2009
  - Requires multi-level, dimming, or automatic shutoff control for most spaces
- ASHRAE 90.1 – 2010
  - Requires multi-level or dimming control for most spaces. No longer excepts spaces that have occupancy sensors
  - Requires automatic multi-level daylighting control for daylit zones, skylight zones> 900 ft^2, and sidelight zones > 250 ft^2
  - Allows increases to the nominal W/ft^2 if advanced controls that meet and exceed mandatory requirements are used

Commercial Energy Codes

- California Title 24 – 2008
  - Requires multi-level or dimming control for spaces > 0.8 W/ft^2
  - Requires automatic multi-level daylighting control for daylit zones > 2,500 ft^2
- California Title 24 – 2014
  - Significant changes to certification, lighting alteration, and lighting controls requirements
  - Multi-level lighting control requirements no longer allow checkerboard/ alternate row switching; each luminaire must comply.
  - Multi-level lighting requirements vary by technology
  - LED luminaires, LED source systems, GU-24 sockets rated for LED require continuous dimming from 10%-100%

Why phase-cut dimming is important for LEDs

- Large U.S. installed base
  - NEMA estimates >150M
  - Mostly "analog" (no neutral)



- Simplest retrofit
  - Replace light source (and maybe dimmer)
  - No new wires
  - No/minimal configuration or commissioning
- Mature control technology
  - Widespread availability
  - Broadest manufacturer and product feature choices
  - Generally most cost-effective

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What's working: Dimming today's LEDs

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Shouldn't this be easy?

Dimmable?

Dimmable!

Shouldn't this be easy?

Future (LED) lighting designer

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LED dimming report card: 2012

Pretty easy to dim	**Still not so easy to dim**

• Architectural, commercial/office, street & area
• New installations, integrated luminaires
  – Especially circuits and systems with “matched” components
• Separate AC power and control (0-10V, DALI)
	• Residential, retail, hospitality, theater
	  – Especially when 1% or less dimming is required
	• Retrofits, replacement lamps
	  – Especially low-voltage (MR16’s) sources
	• Coincident AC power and control (phase-cut)

Successful dimming:
U.S. Department of Labor

Before (HPS)	After (LED + Sensor)
	

- Bi-level (100%, 10%) motion-controlled LED
- 1:1 replacement
- 55% installed wattage reduction
- 77-85% kWh (estimated) energy savings

GATEWAY Demonstrations IN PROGRESS

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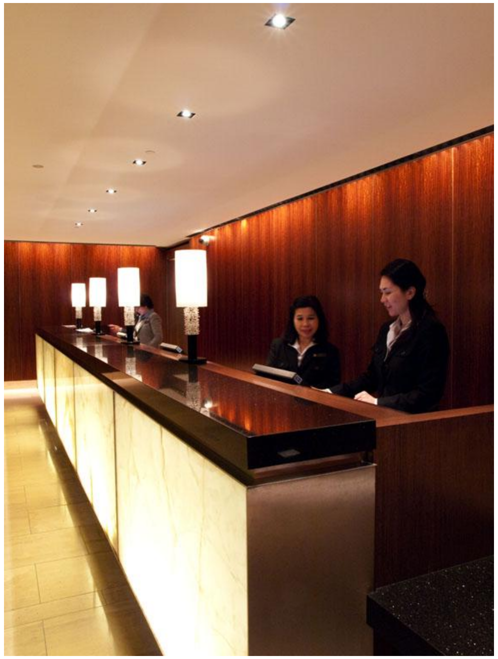
Unsuccessful dimming: Intercontinental Hotel, San Francisco

Before (Halogen)



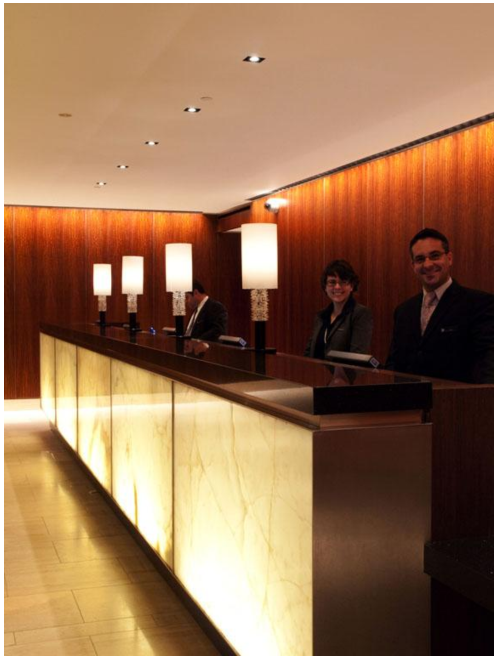
Counter

- 7 x 30W MR16
- 70% day
- 50% night

Walls

- 217 x 20W MR16
- 80% day
- 50% night

After (LED)



Counter

- 7 x 6W MR16
- 100% day
- 100% night

Walls

- 217 x 6W MR16
- 100% day
- 100% night

- Despite dimming problems, project still considered a success
- LED operating power = 33% of halogen on desk, 44% of halogen on walls
- Payback < 2 years

GATEWAY Demonstrations

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Unsuccessful dimming: Smithsonian American Art Museum

Luce Center Gallery of Art, currently lit by 50W MR16 halogen lamps, on electronic transformers, controlled by a preset dimming system.

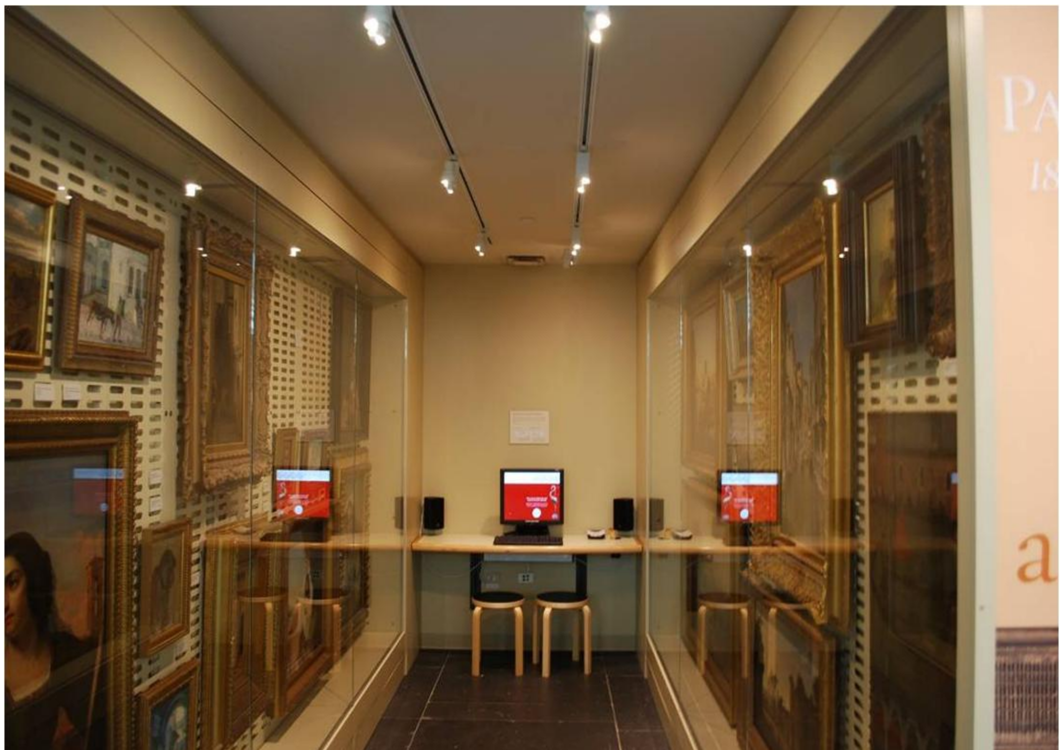
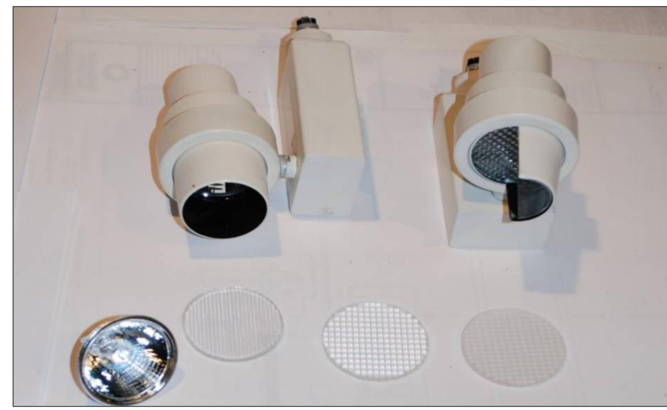


Photo Credit: Scott Rosenfeld



So far, no evaluated MR16 LED replacement lamp can light the gallery without flicker or other poor performance.

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Pretty good examples LED dimming



Some still with a limitation or two…

…requires integral trim
…requires ELV dimmer
…only dims to 20%
…requires specific driver
…increasing flicker as dimmed
…requires specific transformers
…low light output for category
…requires 0-10V dimmer

And some pushing boundaries…
…dims to warm
…no flicker or color shift as dimmed





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Old vs. new world of dimming

Old world lighting technologies

- Dimmable
  - Incandescent, halogen
- Somewhat dimmable
  - Linear fluorescent
  - Compact fluorescent
- Not very dimmable
  - Mercury vapor
  - Metal halide
  - High-pressure sodium
  - Low-pressure sodium



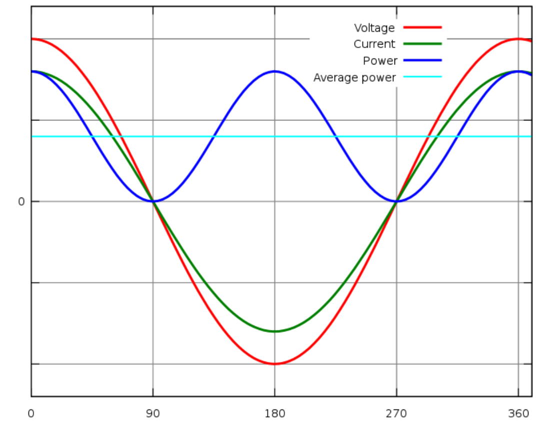




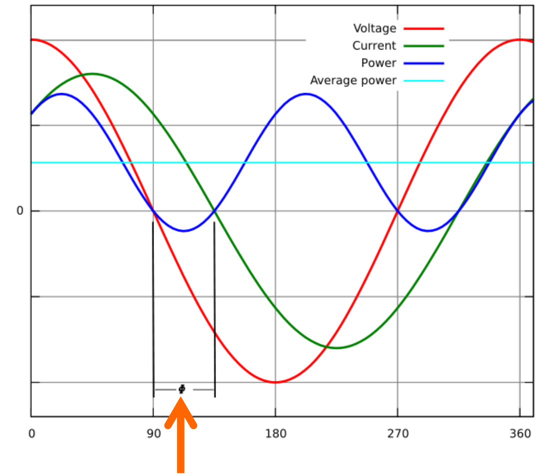
Power factor

- Real, Active, True Power (P) measured in Watts
- Reactive Power (Q) measured in VAR
- Apparent Power (S) measured in VA
- $S^2 = P^2 + Q^2$
- Power Factor relates Active Power and Apparent Power by PF = P/S
- For loads with PF = 1, all supplied power is consumed by load
- For loads with PF < 1, some supplied power is consumed by load; some is stored and returned to the system
- Low(er) power factor loads do NOT consume more energy, BUT they do draw more RMS current

Simple example of PF =1



Simple example of PF <1

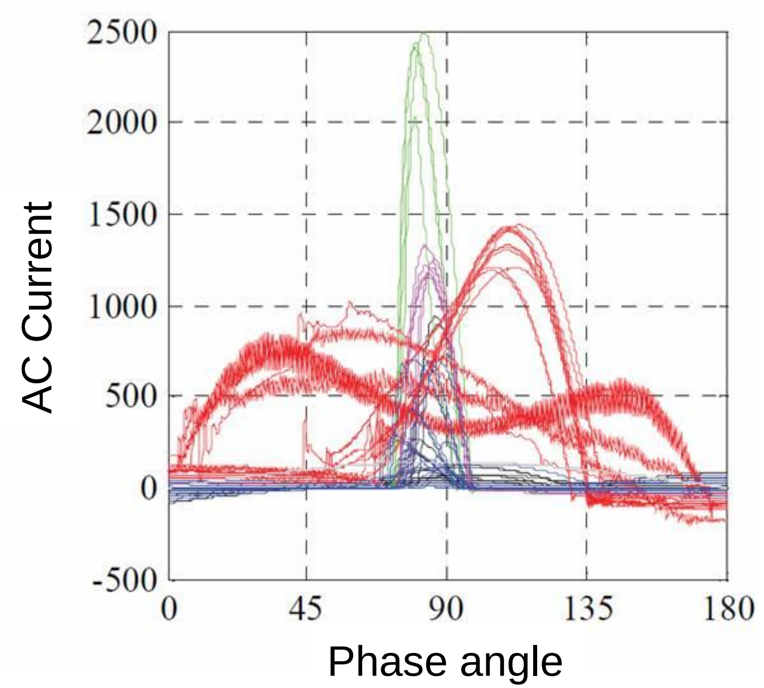


Displacement only

Old world power factor

- PF = 1
  - Incandescent, halogen
- Typically High PF
  - Linear fluorescent
  - Metal halide
- High to Low PF
  - High-pressure sodium
  - Low-pressure sodium
  - Compact fluorescent
  - Mercury vapor

Examples of distorted input current for electronic power supplies



Flicker

What are we talking about?

- Modulation of light output (luminous flux)
- Present in all commercial electric light sources (whether you are aware of it or not)
- Typically (but not always) periodic, and property of light source
- Not to be confused with “electrical flicker”
  - Noise on AC distribution line directly creates additional (light) modulation on resistive (incandescent) loads
  - Not a property of the light source

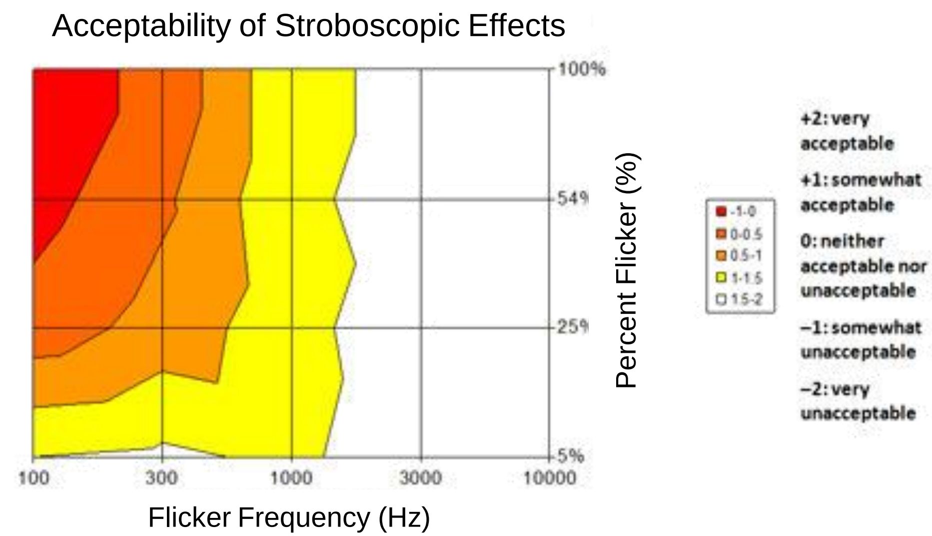
Flicker

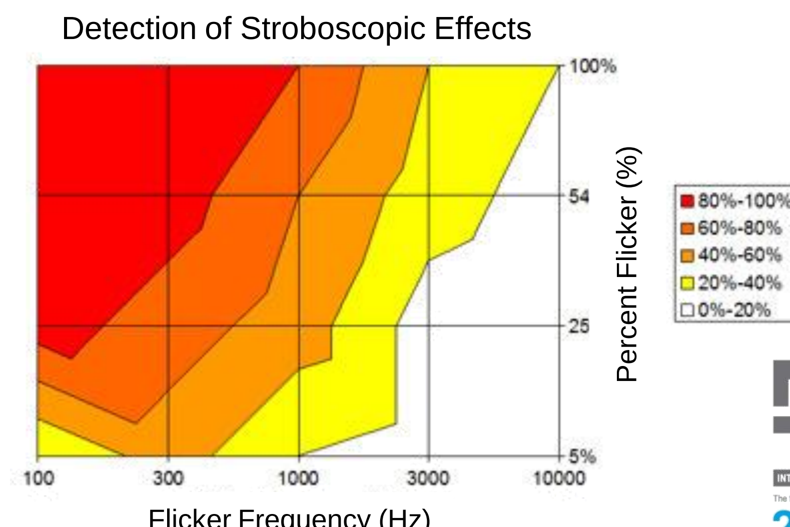
Who cares?

- Lighting designers and anyone responsible for human performance in built environment
- Varying population susceptibility, risk levels for different lighting conditions
- Implications
  - Neurological problems, including epileptic seizure
  - Headaches, fatigue, blurred vision, eyestrain
  - Apparent slowing or stopping of motion
  - Reduced visual task performance
  - Distraction

Mitigating the effects of flicker

- Degrees of mitigation
  - Detection
  - Objection
  - Implication(s)
- All other things being equal
  - Higher modulation frequency results in reduced effects
  - Lower modulation depth results in reduced effects
  - Lower duty cycles results in increased effects
  - Greater eye motion results in increased effects





Source: http://www.lrc.rpi.edu/programs/solidstate/assist/flicker.asp

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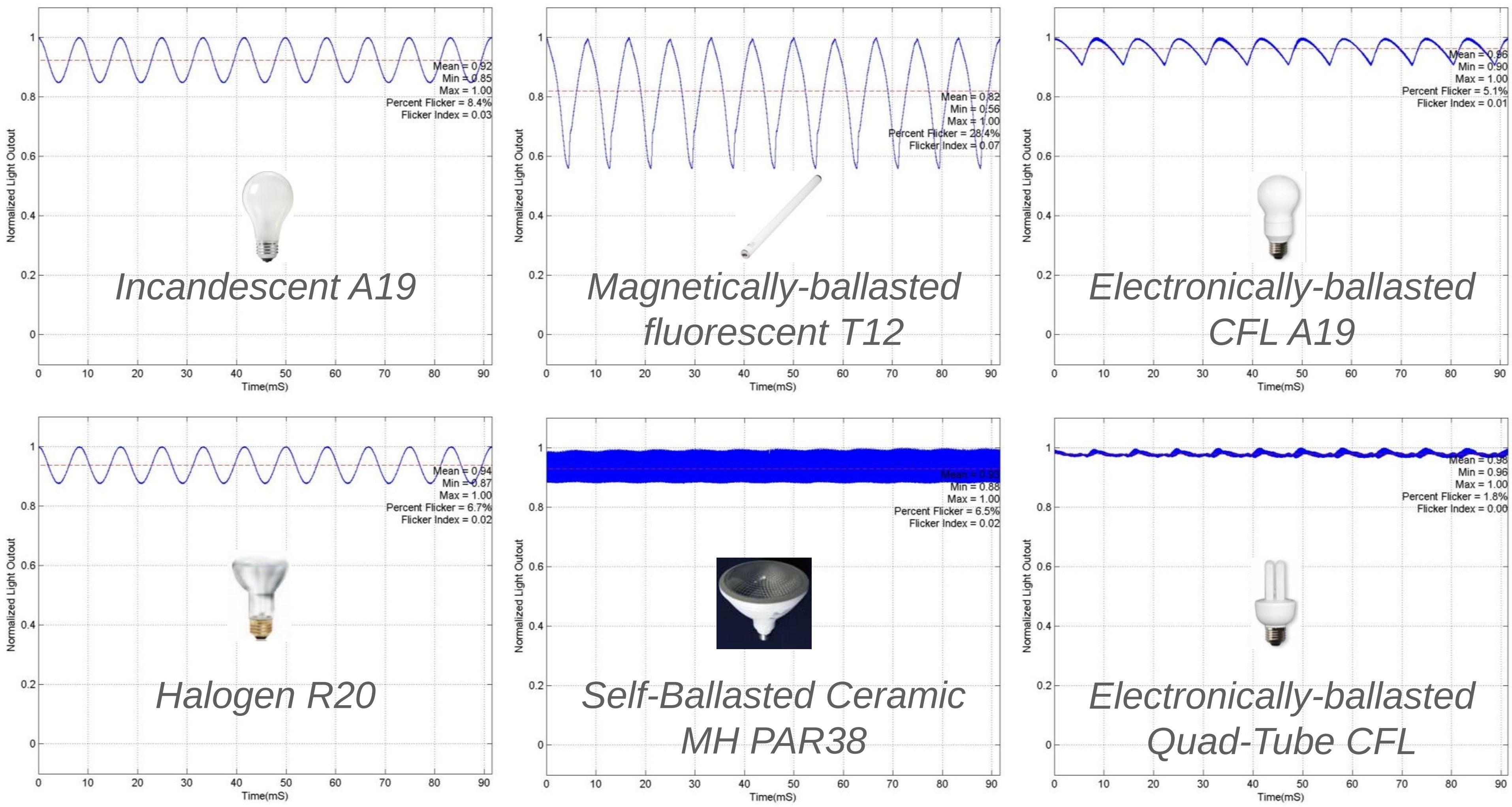
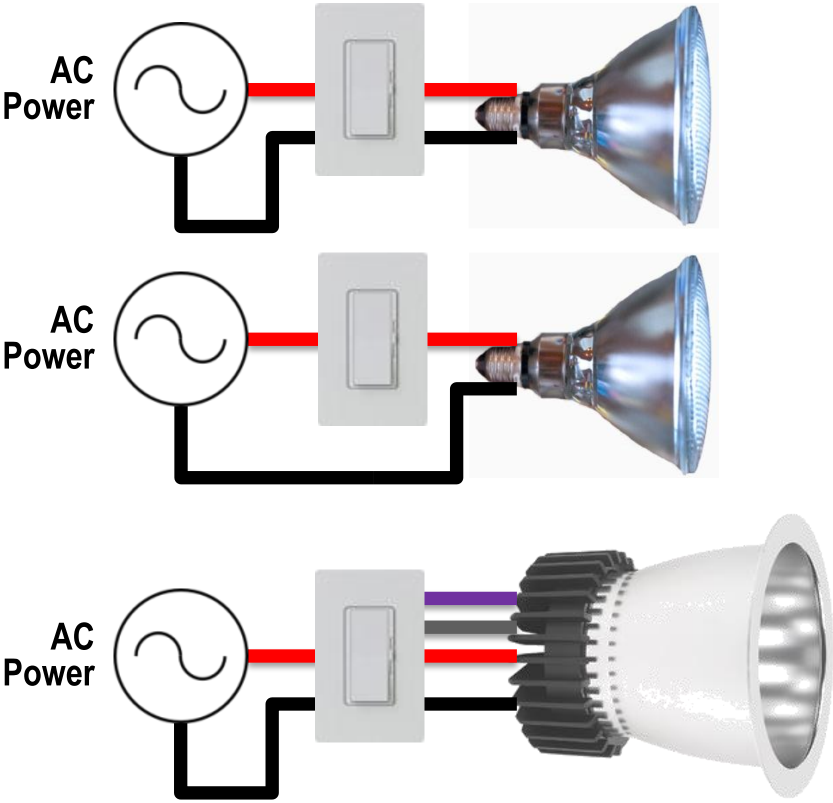
Old world flicker



Two approaches to dimming

- Coincident AC power and control signal
  - Reduce amplitude of AC sine wave
  - Phase-cut AC sine wave
- Separate AC power and control signal
  - One-way communication
  - Two-way communication



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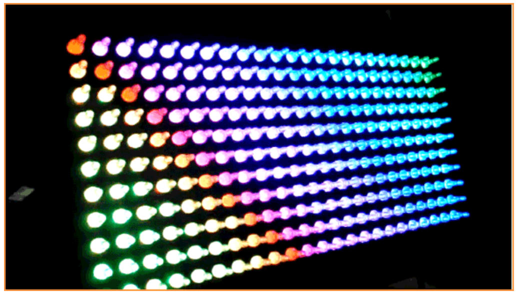
Old world dimming technologies

Coincident AC power and control signal

- Sine wave (long obsolete)
- Phase-Cut
  - Forward phase or reverse phase
  - 2-Wire (hot, dimmed hot) or 3-Wire (hot, dimmed hot, neutral)

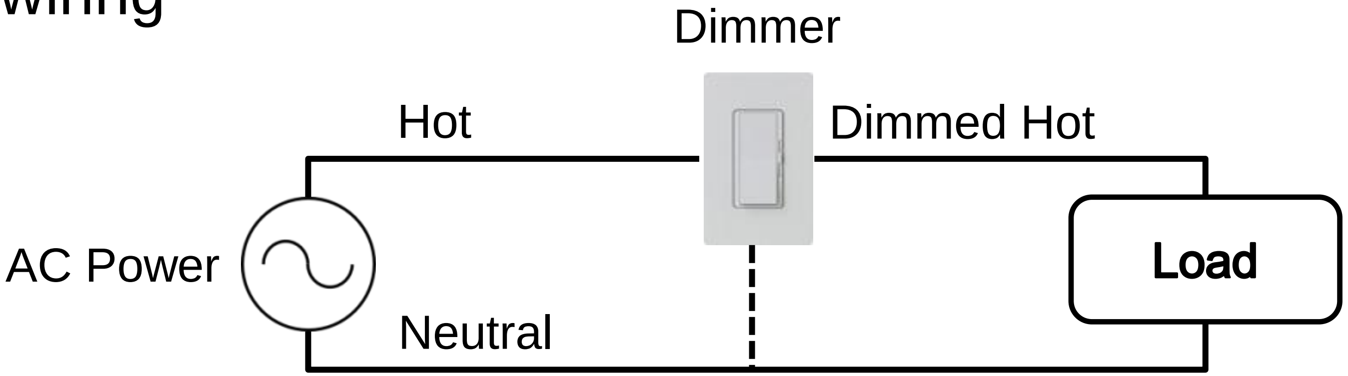
Separate AC power and control signal

- Fluorescent 3-Wire
- 0-10V
- DALI
- DMX512



Phase-cut overview

- Coincident AC power and control signal
- One-way communication
- Originally developed in 1960's for incandescent lighting
- No new wires required for basic control
  - Neutral wire sometimes required for advanced control, features
- Impossible to assign individual control devices (dimmers, sensors) to one or many light sources without added wiring



Phase-cut features and challenges

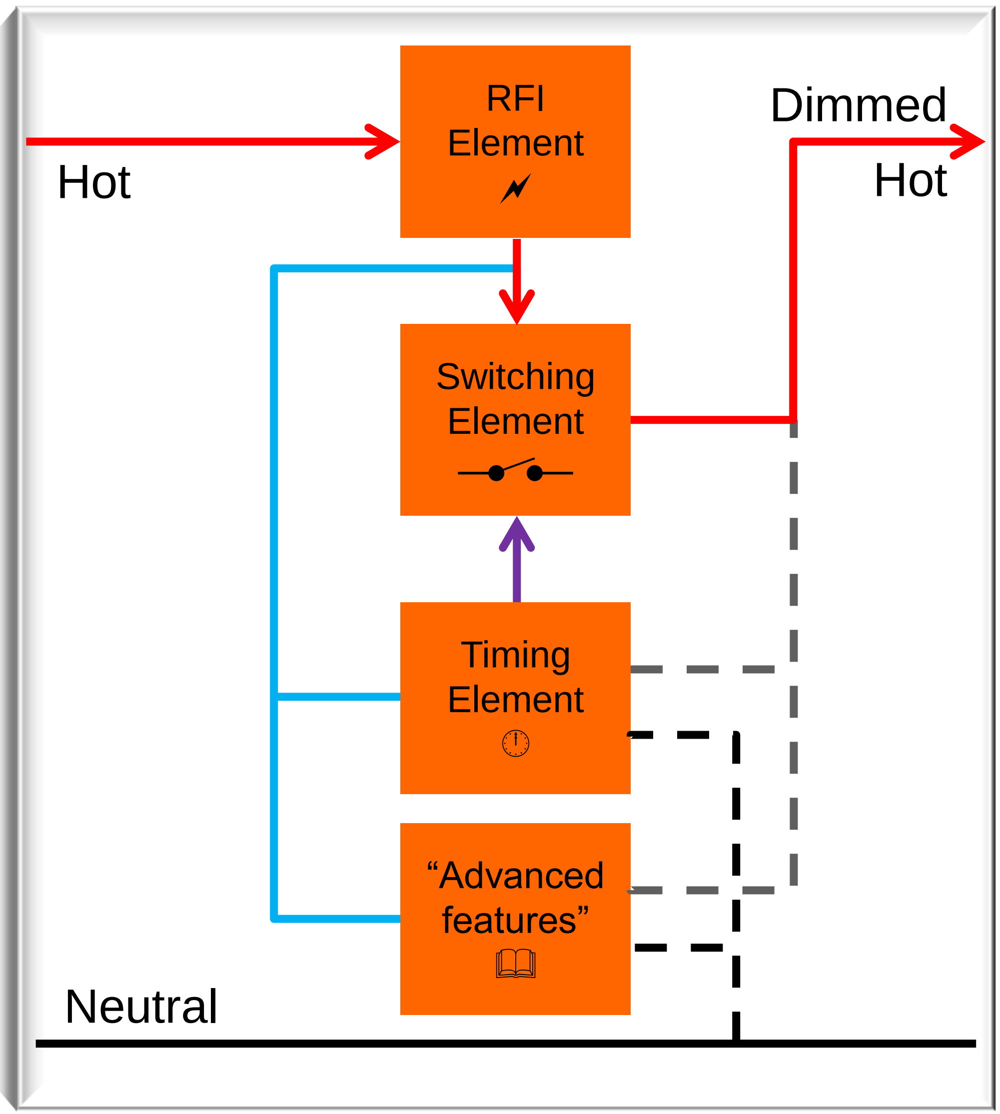
Features

- Simplest retrofit
- Most cost-effective solution
- No/minimal configuration or commissioning
- Widespread availability
- Broad manufacturer and product feature choices

Challenges

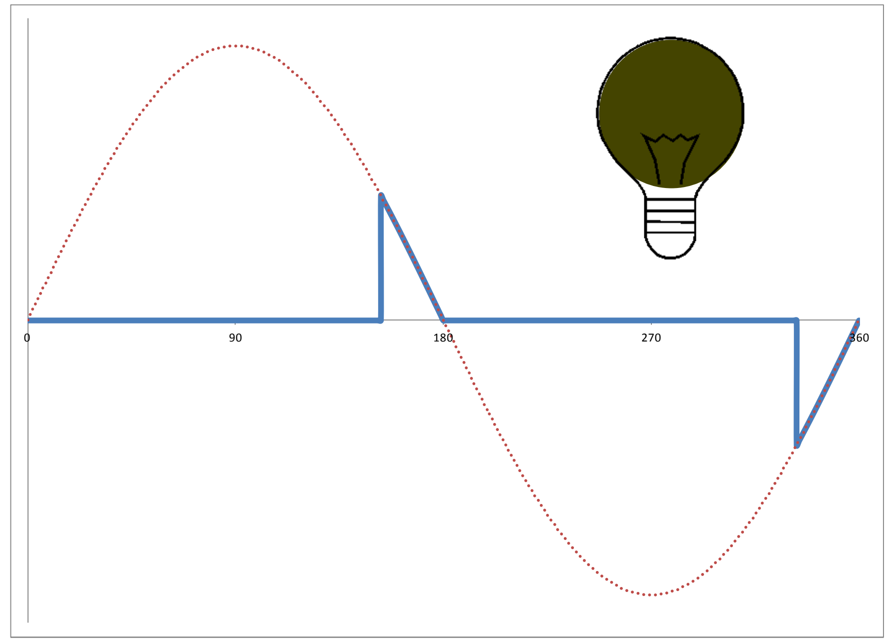
- Dimmer load restrictions
  - Typical minimum load is 10-40W
  - Typical maximum load of 600W, 1000W, or 2000W
- Not ideally suited for technologies other than incandescent

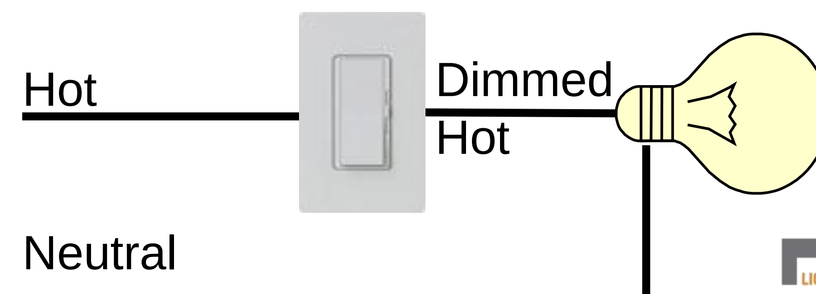
Anatomy of a phase-cut dimmer



Forward phase-cut dimming

- Most common dimming method
- Largest (by far) installed base
- Designed for resistive (incandescent, halogen) or magnetic low-voltage (MLV) loads
- Typically a TRIAC switching device, but may use Field-Effect Transistors (FETs)
- Low cost, simple designs





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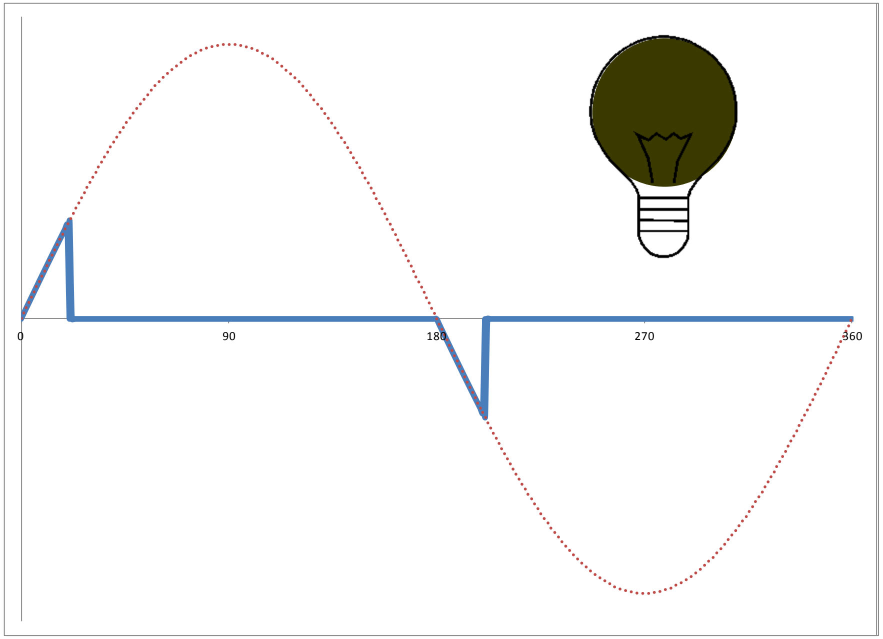
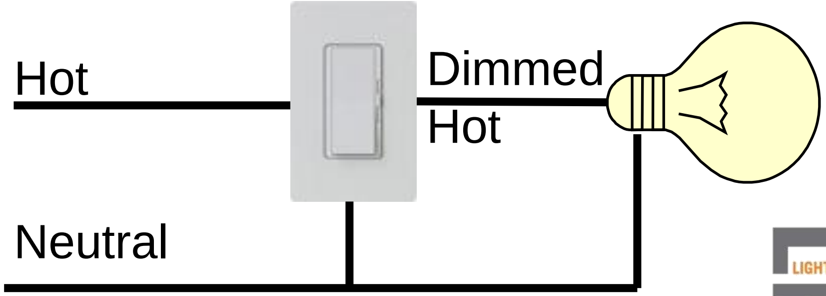
Reverse phase-cut dimming

- Much smaller installed base
- Nearly always requires a neutral wire
- Designed for Electronic Low-Voltage (ELV) systems
- Field-Effect Transistor (FET) or similar switching device

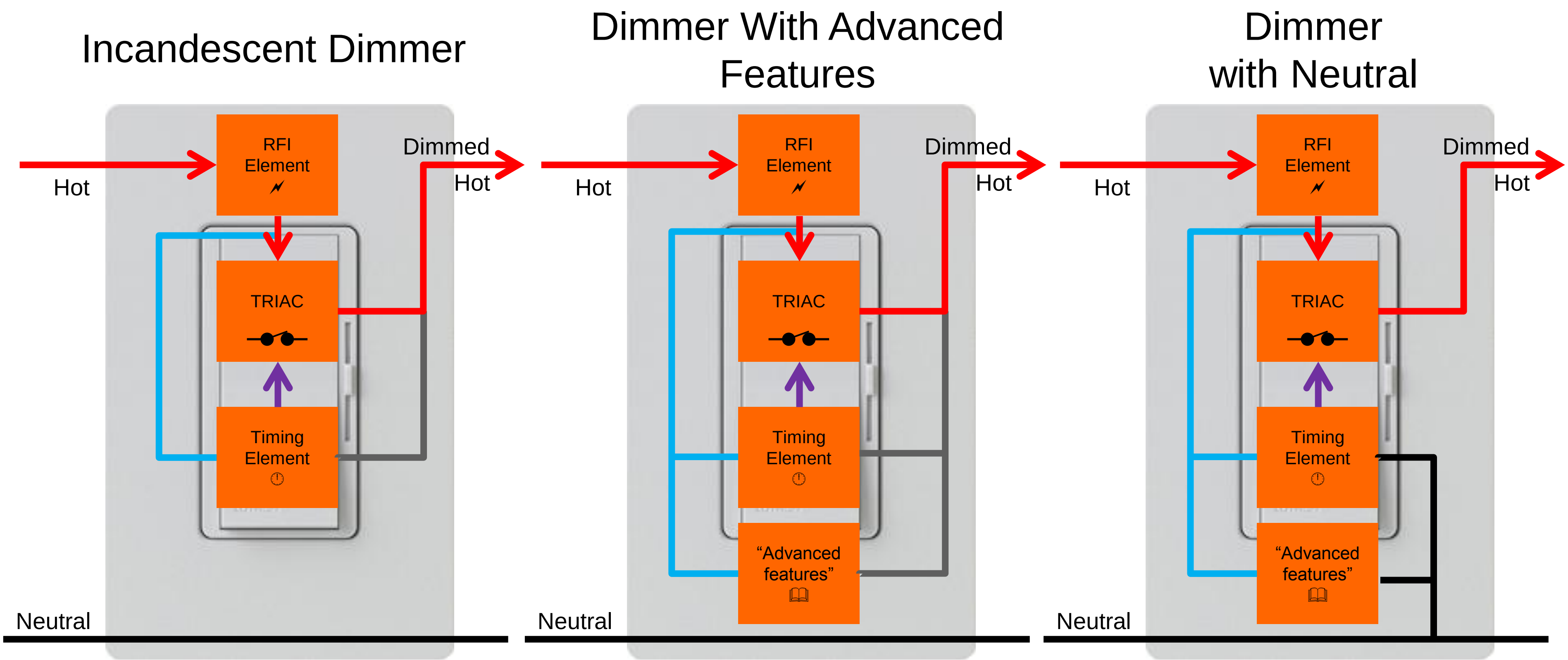




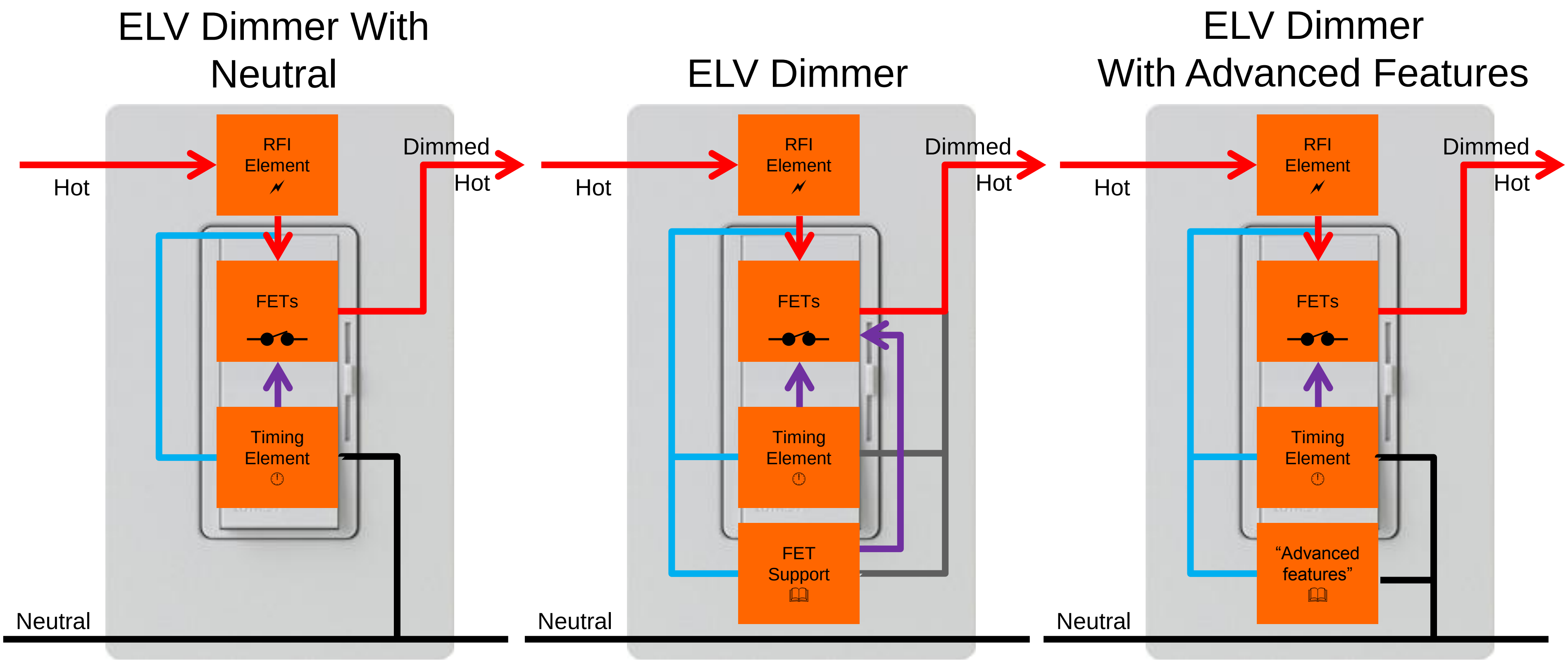
Standard phase-cut dimmer terminology?

What it says	What it (typically) means
1. Incandescent or Resistive	1. For incandescent or halogen sources
2. Inductive or Magnetic	2. For low-voltage magnetic transformer (MLV) systems
3. Electronic or Capacitive	3. For low-voltage electronic transformer (ELV) systems
4. Digital or Microprocessor	4. Has microprocessor and advanced features
5. Analog or Electromechanical	5. Doesn't have microprocessor or advanced features
6. Low-Voltage	6. MLV, ELV …. or 0-10V!
7. Preset	7. Can turn on directly to previous level, or fixed pre-set levels, or user selected pre-set levels

Forward phase-cut dimmer examples

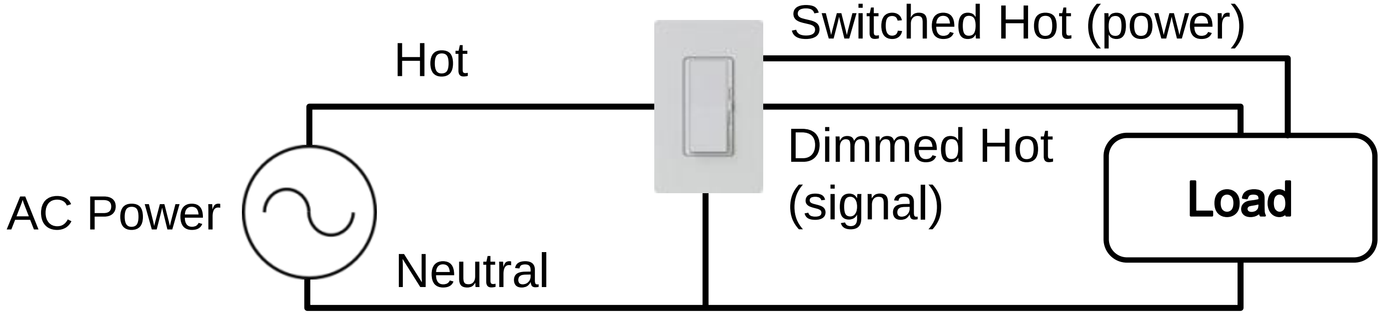


Reverse phase-cut dimmers



Fluorescent 3-Wire overview

- Separate AC power and control signal
  - Phase-cut hot control signal
- One-way communication
- Developed in 1970's for high quality linear fluorescent systems
- Requires one extra AC line voltage (phase-cut hot) wire, which can be run in same Class 1 conduit as hot wire
- Impossible to assign individual control devices (dimmers, sensors) to one or many light sources without added wiring



Fluorescent 3-Wire features & challenges

Features

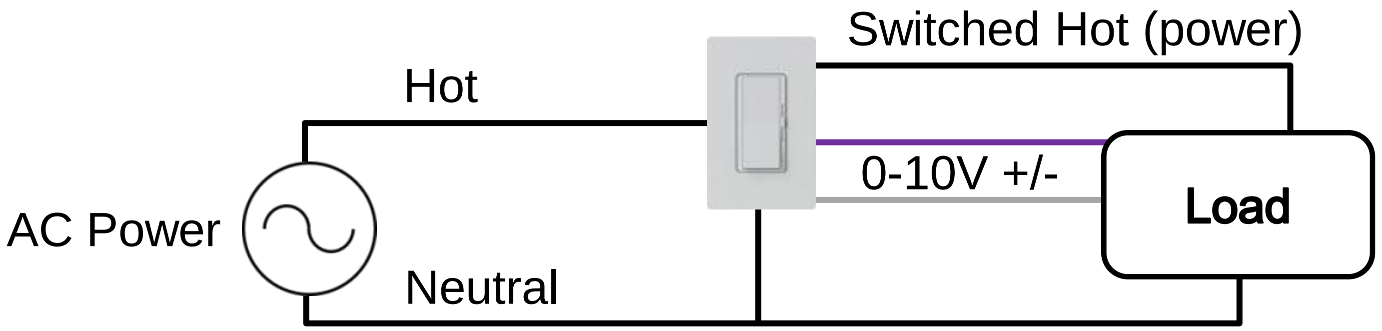
- Stable over long wire runs
- No degradation in AC line power quality when dimmed

Challenges

- Ad-hoc standard, but fairly interoperable
- Sometimes confused with phase-cut “3-Wire dimmers”
  - Fluorescent 3-Wire: hot, switched hot, dimmed hot
  - Forward or reverse phase 3-Wire : hot, dimmed hot, and neutral

0-10V overview

- Separate AC power and control
- One-way communication
- Actually two “standards”
  - ANSI E1.3, originally developed by the Entertainment Services and Technology Association (ESTA) in 1997 for theatrical equipment
  - IEC 60929, originally released in 1992 for linear fluorescent systems
- Requires two low-voltage differential wires per control channel, which carry a low-speed signal, directly connected between each control and load
- Impossible to assign individual control devices (dimmers, sensors) to one or many light sources without added wiring



0-10 Volt features and challenges

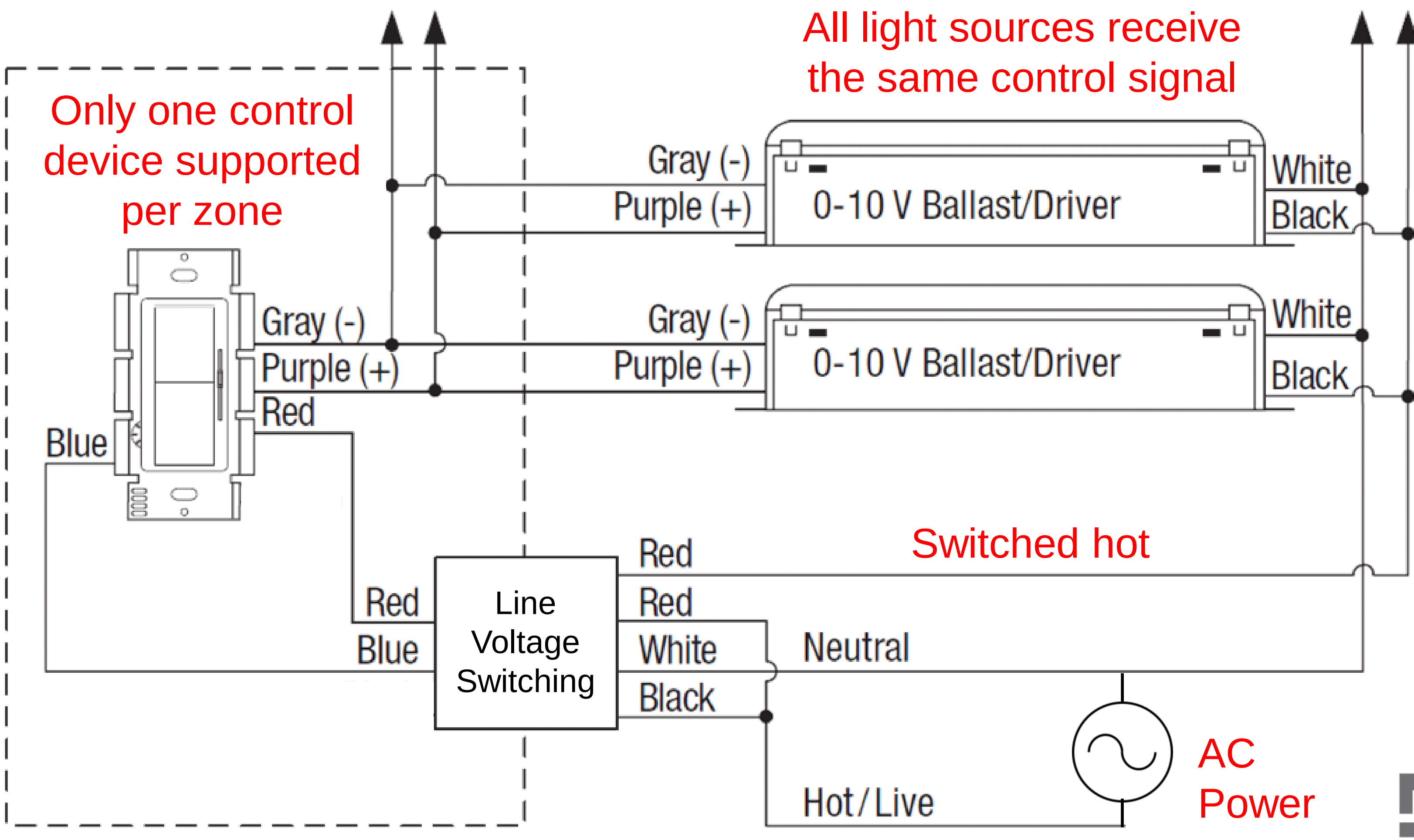
Features

- Cost-effective control
- Control zones can be run separate from power zones
- Few interoperability problems when all components comply with same “standard”

Challenges

- Typically (not always) requires line-voltage switching
- Costly wiring requirements
- Long wire runs can affect performance (e.g. dimming range, accuracy)
- “Standards” do not specify whether controls signals should be run as UL Class 1 or Class 2
- Unknowing use of components complying with different “standards” results in interoperability problems

Typical 0-10V system architecture



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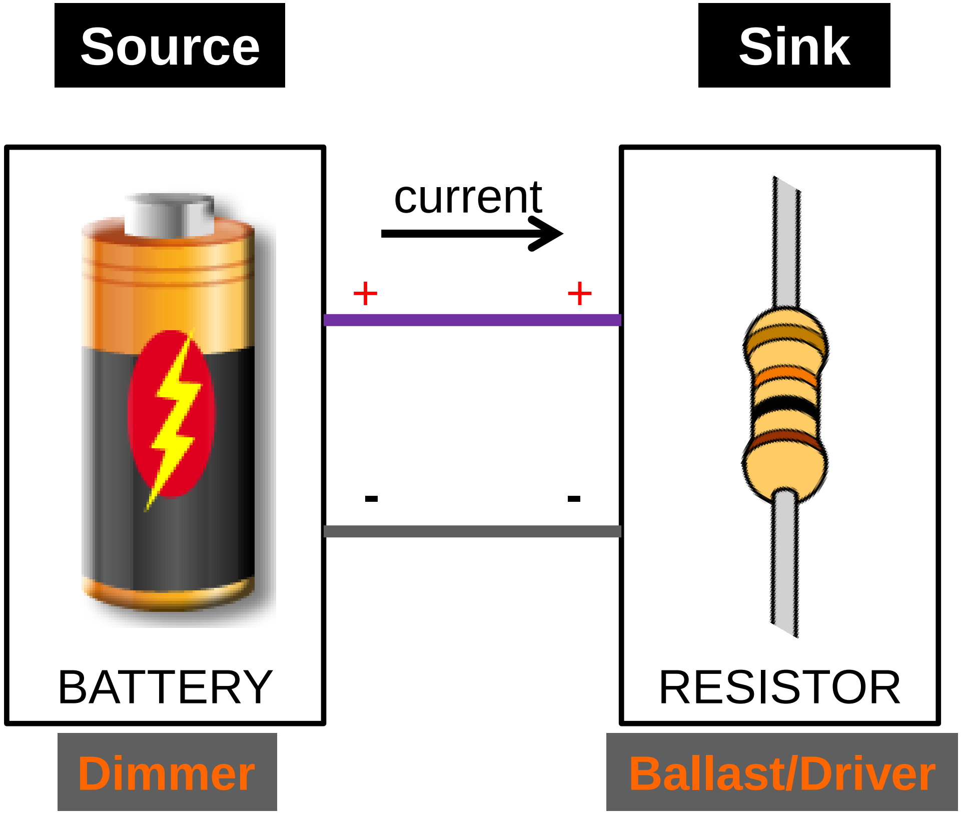
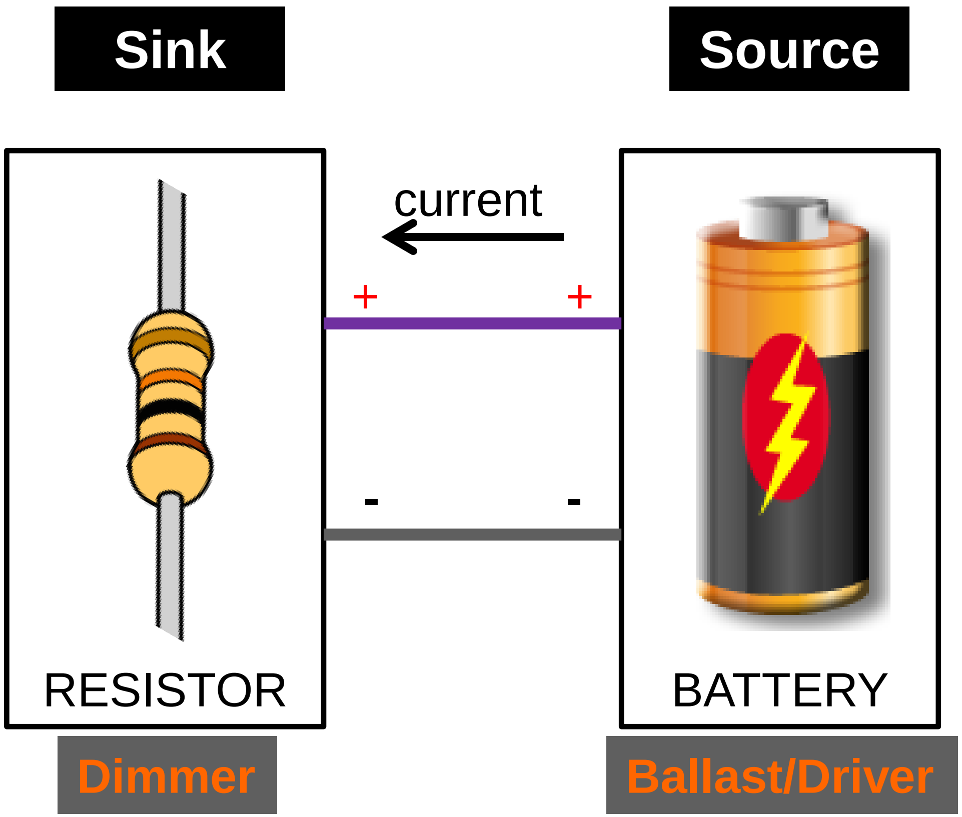
0-10V using ANSI E1.3

- What it defines:
  - The control sources the current
  - The load sinks the current
  - 10V = 100% light
  - 0V is off
- Compliant light sources not compatible with most general lighting controls



0-10V using IEC 60929

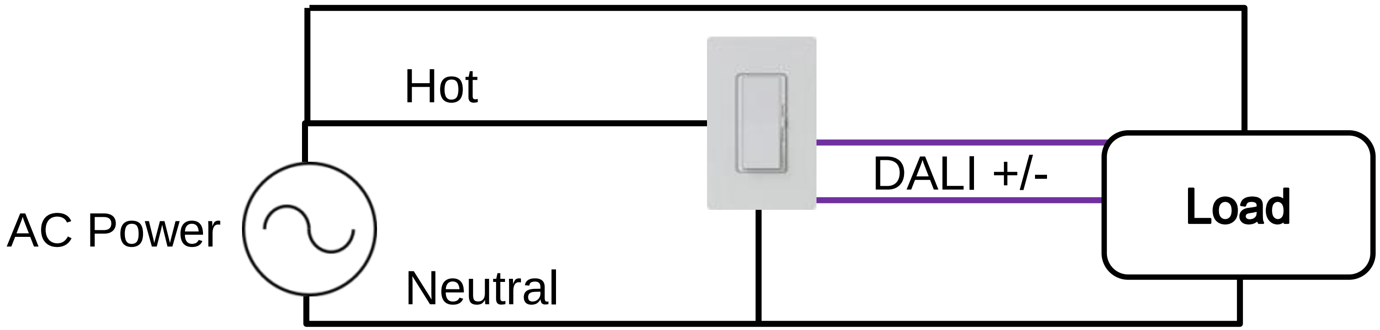
- What it defines
  - The load sources the current
  - The control sinks the current
  - 10V or above = 100% light
  - 1V or below = minimum light
- No definition of dimming performance, lifetime, etc.



Revision history: 60929:1992, 60929:2004, 60929:2006, 60929:2011

DALI overview

- Two-way communication
- Originally developed in 1990's as part of IEC 60929 for linear fluorescent systems
  - Recently removed, expanded and turned into IEC 62386
- Requires two low-voltage differential wires which carry a low-speed signal, daisy chained across one or more devices
- Easy to assign individual control devices (dimmers, sensors) to one or many light sources without added wiring



DALI features and challenges

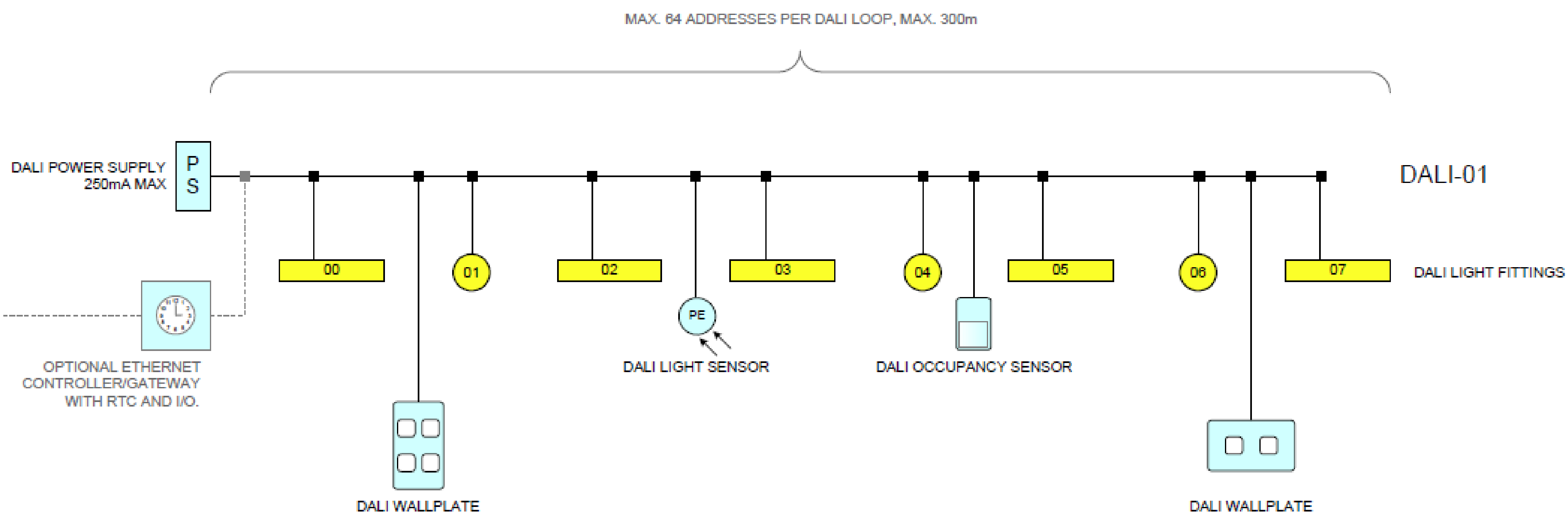
Features

- Single interface for Electronic Control Gears and Electronic Control Devices
- Addressing of up to 64 individual components per DALI link, at data rates of 1200 bits/second
- Allows control and status reporting of wide variety of ballasts, dimmers, sensors
- Presumes that control signal is run as UL Class 1 (with AC)

Challenges

- Many manufacturers have “proprietary” extensions, resulting in interoperability problems with components from other manufactures
- Typically time-consuming and complex commissioning
- Some manufacturers run control signal as UL Class 2

Typical DALI system architecture



Standard does not allow multiple “masters” per system.
Varying “extended” DALI standards may, however.

DMX512 overview

- One-way communication (RDM added feedback)
- Originally developed by the US Institute of Theater Technology and released in 1988 for theatrical applications – specifically RGB light sources
- Standardized as ANSI E1.11-2008 “DMX512-A - Asynchronous Serial Digital Data Transmission Standard for Controlling Lighting Equipment and Accessories”
- Requires two low-voltage differential wires which carry a high speed signal, daisy-chained across one or more devices
- Easy to assign individual control devices to one or many light sources without added wiring.
- Available in wireless implementations as well (WDMX)

DMX512 features and challenges

Features

- Serial data stream sent over a balanced cable system connected between a data transmitter and a data receiver.
- Addressing of up to 512 channels per data link or “universe”, at data rates of up to 250 kbits/second
- Systems typically consist of a one or more data transmitters (typically a lighting console) connected to a variety of data receivers

Challenges

- Requires unique wiring and wiring practices
- Complex addressing and programming of multiple channels
- Typically costly controls, luminaires, and wiring
- Can create mixed-color white, but not well suited for general lighting

Typical DMX512 system

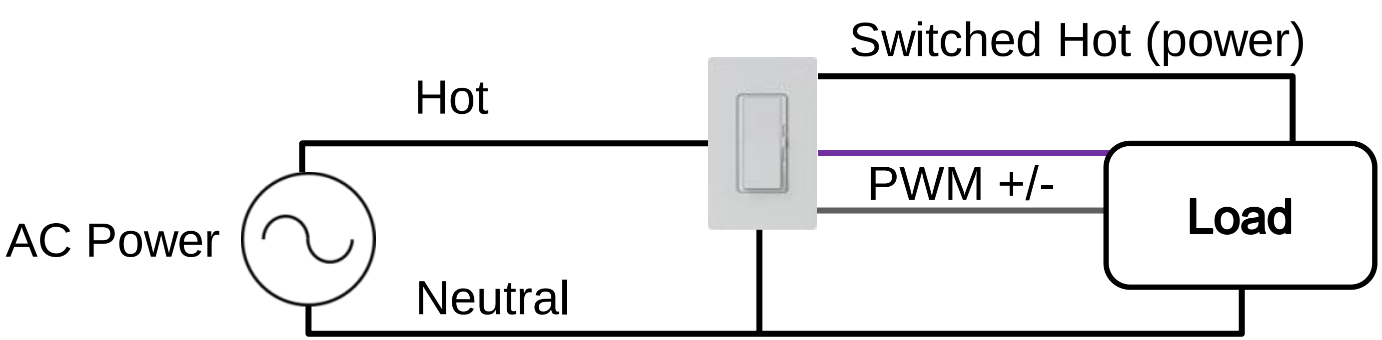
DMX512 Lighting Console

DMX data receivers

- Dimmers, control gear
- Mechanical color changers
- Color changing light sources
- Lasers, strobes
- Smoke, confetti machines, other theatrical devices

PWM

- Separate AC power and control signal
- Analog one-way communication
- Originally developed for linear fluorescent systems as part of IEC 60929 (Annex E)
- Requires two low-voltage wires which carry a pulse-width encoded 1kHz signal
- Impossible to assign individual control devices (dimmers, sensors) to one or many light sources without added wiring



PWM features and challenges

Features

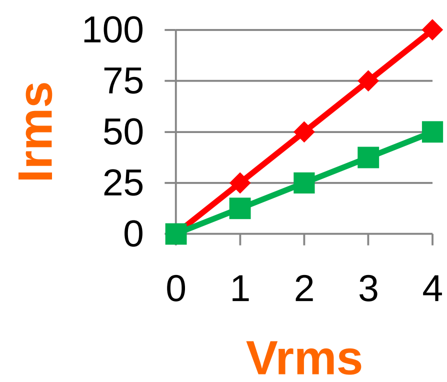
- Cost-effective control
- Control zones can be run separate from power zones
- Less sensitive to long wire runs

Challenges

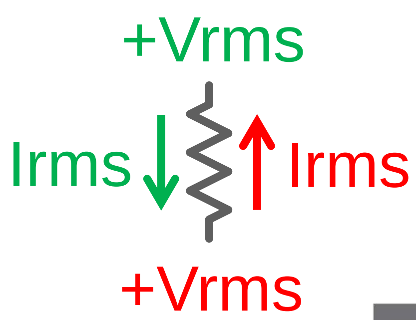
- Typically requires line-voltage switching
- Costly wiring requirements
- Primarily adopted in Japan; rarely found elsewhere, so fewer equipment options

Controlling current in simple (resistive) loads

- Resistive loads have linear current-voltage relationships
  - $I = (1/R) \times V$
  - For AC input, only care about Vrms
  - Time independency: $I_{rms} = (1/R) \times V_{rms}$

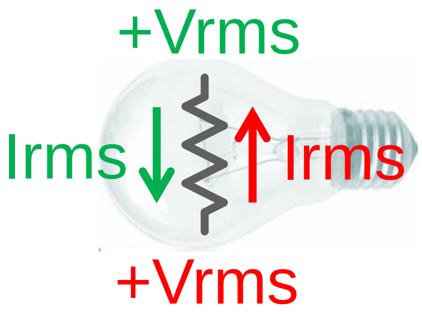


- Resistive loads are bidirectional
  - Applying ±Vrms results in the same Irms
  - $I_{rms} = (1/R) \times |V_{rms}|$



Incandescent sources are simple (resistive) loads

- Incandescent sources electrically behave like resistors (unlike pretty much every other lighting technology)
- Incandescent sources effectively only care about Vrms
  - Constant R at steady state
  - R is a function of filament temperature
- Incandescent sources are bidirectional
  - Applying ±Vrms results in the same Irms
  - Irms = (1/R) x |Vrms|
- Important caveat: thermal persistence
  - If I(t>0)→0 in resistor, no power consumption
  - If I(t>0)→0 in incandescent source, light output continues as long as filament is hot (10s to 100s of milliseconds)



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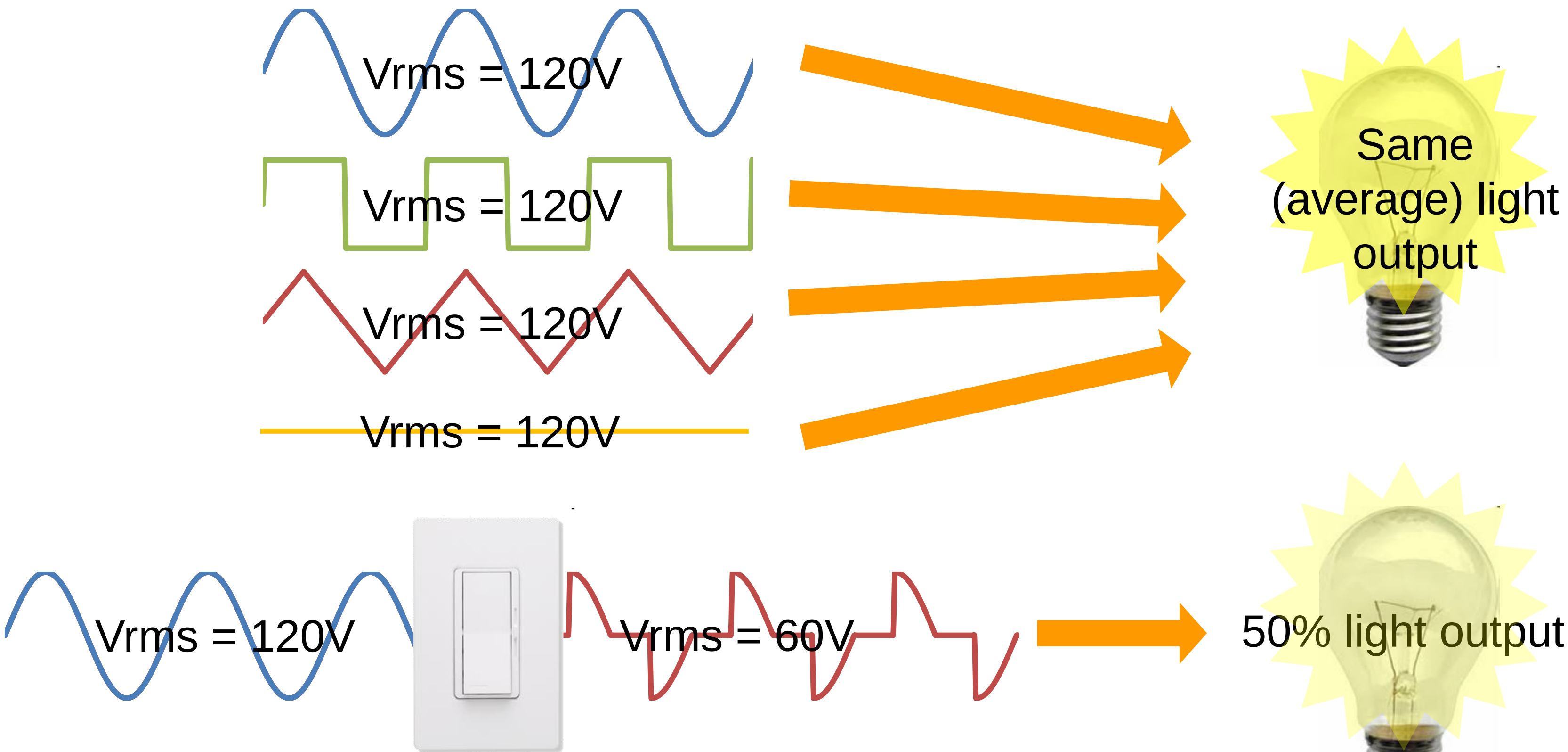
Dimming incandescent sources

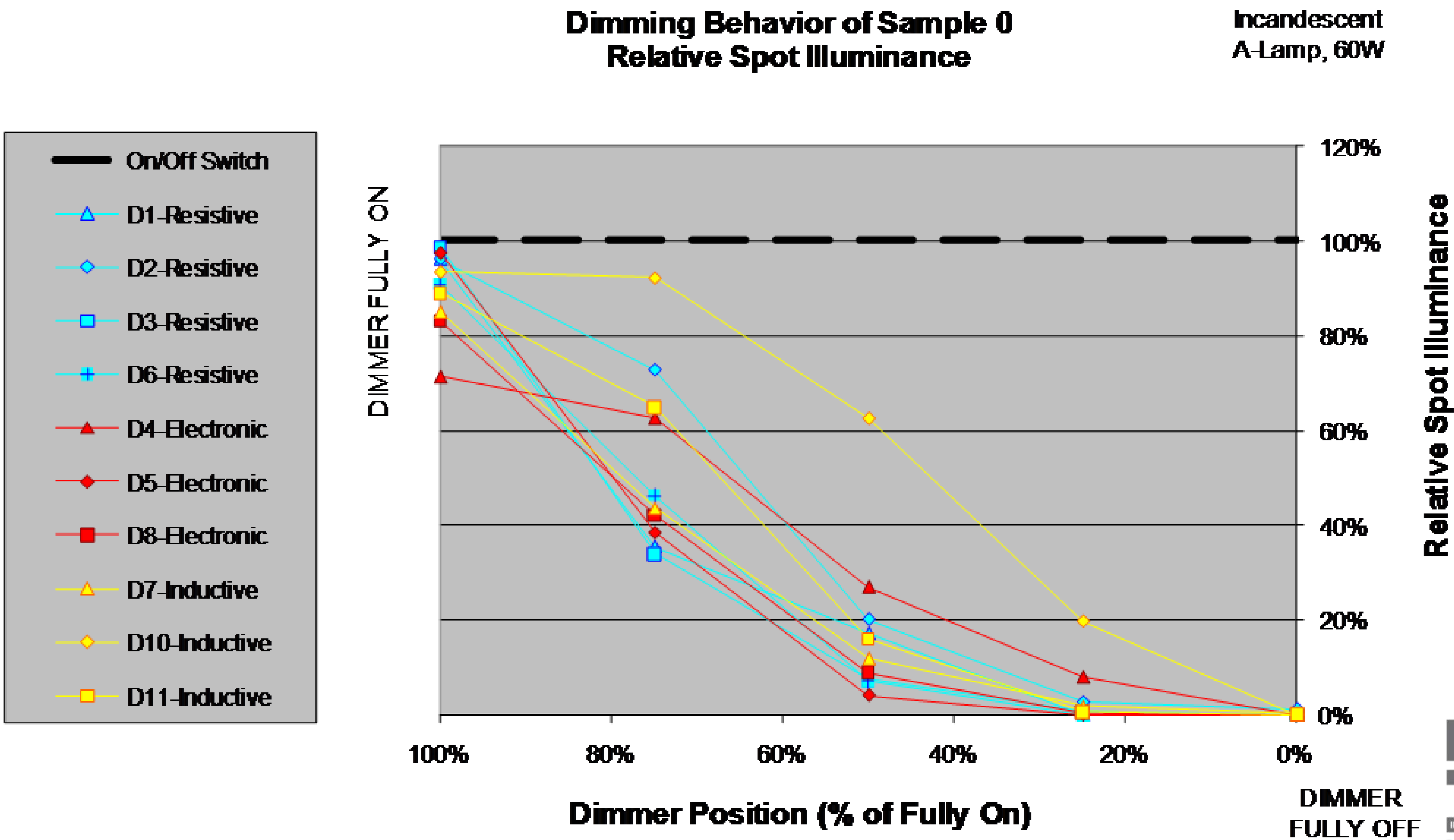
- Inherently dimmable (don’t need to specify “dimmable”)
- Compatible with all phase-cut dimmers
- Dimmable to less than 1% on all phase-cut dimmers
- Smooth dimming
- Shift in color towards warmer white, lower CCT, reddish chromaticity as they dim
- Thermal persistence of filament minimizes flicker

Controlling incandescent light output

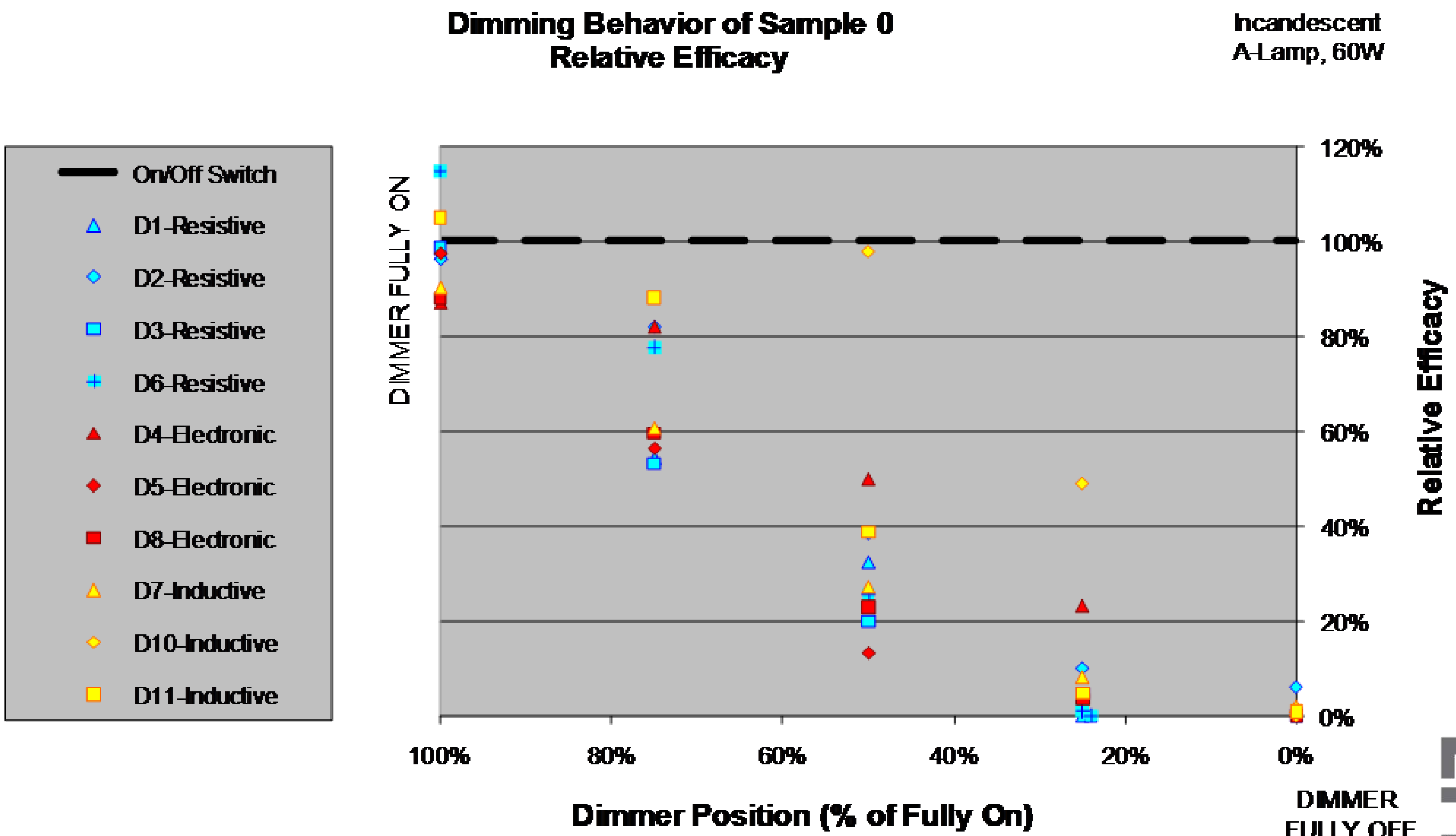


High performance
Inexpensive
Vrms adjuster
Determines dimming performance!

Incandescent sources have similar dimming curves with different phase-cut dimmers



Incandescent sources lose efficacy when dimmed

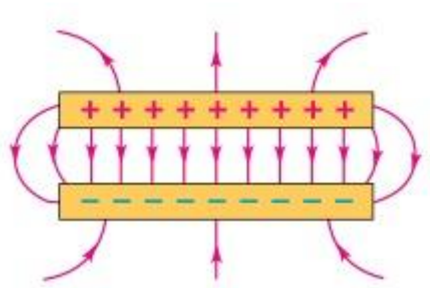


Summary: Dimming in the old world

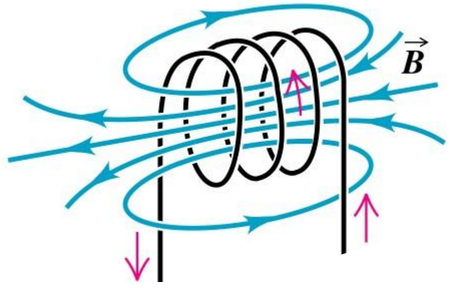
- The majority of the dimmed lighting in the existing built environment consists of incandescent sources on phase-cut dimmers
- The majority of phase-cut dimmers installed in the existing built environment were designed to dim incandescent light sources using forward phase-cut, TRIAC based circuitry
- “Dimmable” means dims like an incandescent source
- Dimming curves and other dimming performance features determined solely by dimmer design

Controlling current in complex loads

- Complex loads contain complex electronic devices (e.g. capacitors, inductors)
- Complex loads contain devices which store energy
- Complex loads contain devices with non-linear current-voltage relationships
- Complex loads contain devices with time-dependencies (e.g. dv/dt, di/dt, on/off switching)



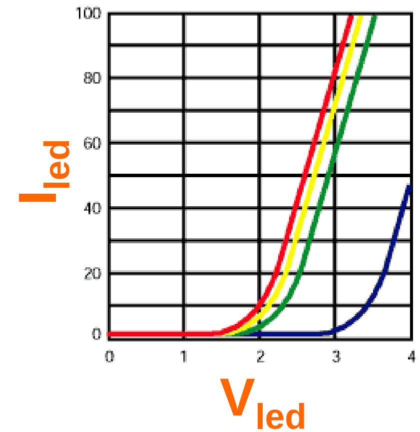
Capacitors store energy in electric fields

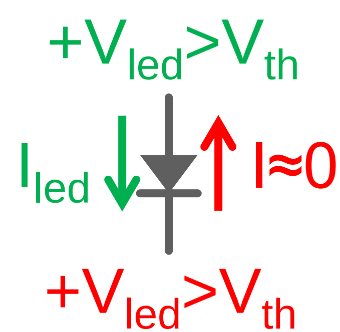


Inductors store energy in magnetic fields

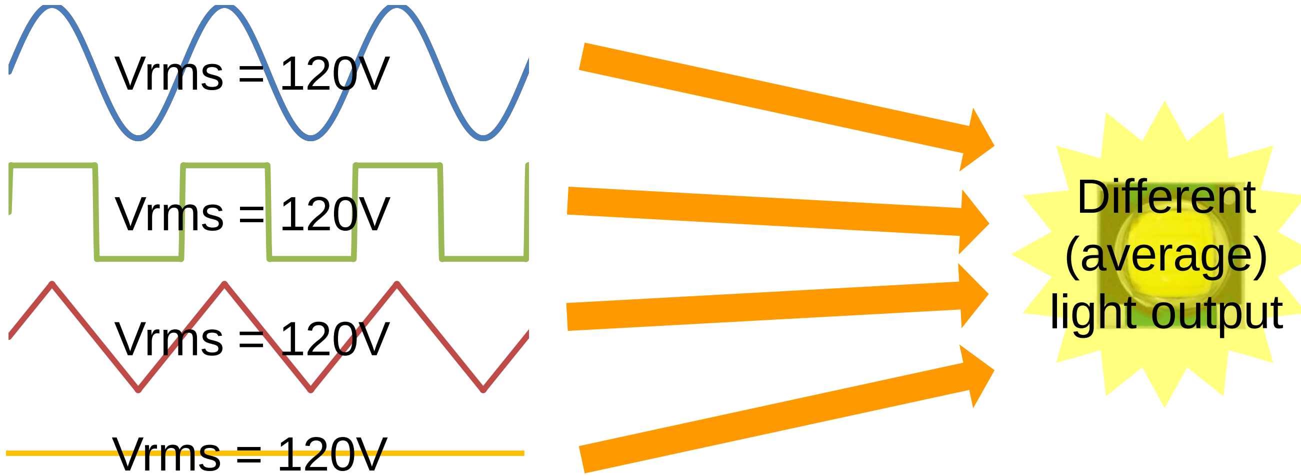
LEDs are complex loads

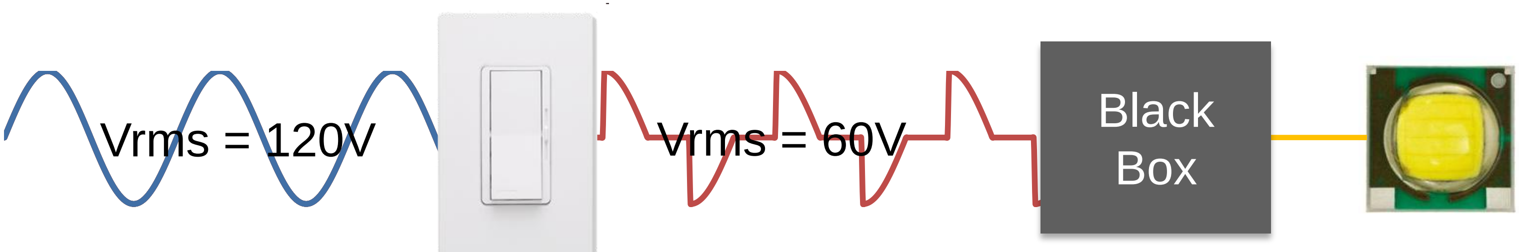
- LEDs are non-linear devices
  - Different current-voltage relationships in different regions of operation
  - Small change in voltage can equal large change in current
  - (Average) current must (typically) be controlled
- LEDs are unidirectional
  - (Forward) current only flows in one direction
  - Light output only for forward current
- Important caveat: fast response
  - If I(t>0)→0 in diode, no power consumption
  - If I(t>0)→0 in LED, no light output
  - Careful attention to time where I≈0





Controlling LED light output





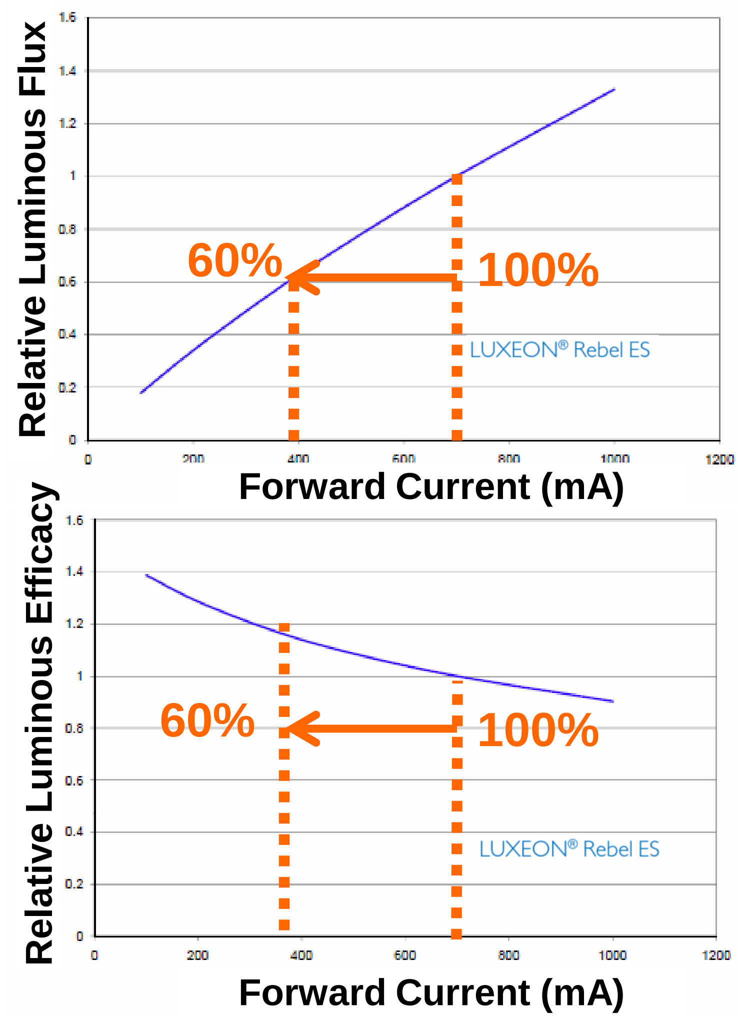
High performance
Inexpensive
Vrms adjuster

Controls current to LED
Determines dimming performance!

LEDs ARE easy to dim!

Constant Current Reduction (CCR, or Analog)

- Varying LED current, LED always on
- Longer LED lifetime
  - Lower current and temperature
- No noise generation
- Potentially higher efficacy at lower dimming (lower current) levels
- Does not create flicker
- Objectionable color shift?
- More difficult dimming regulation at deep dimming (low current) levels



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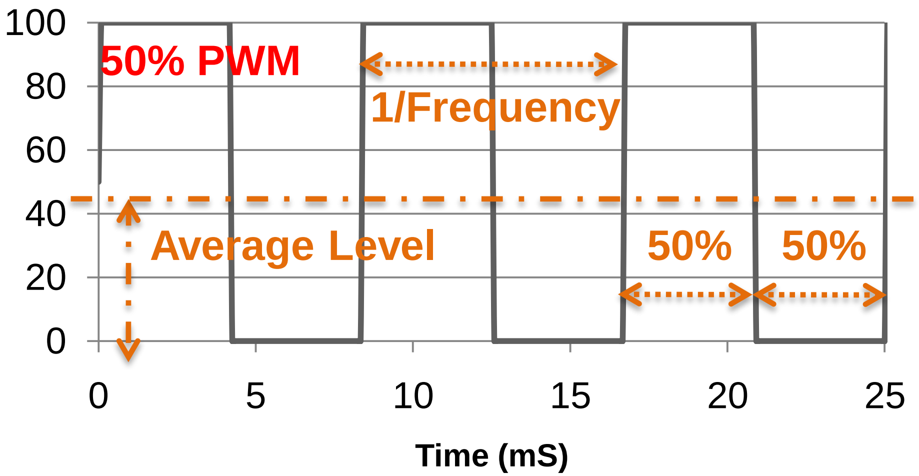
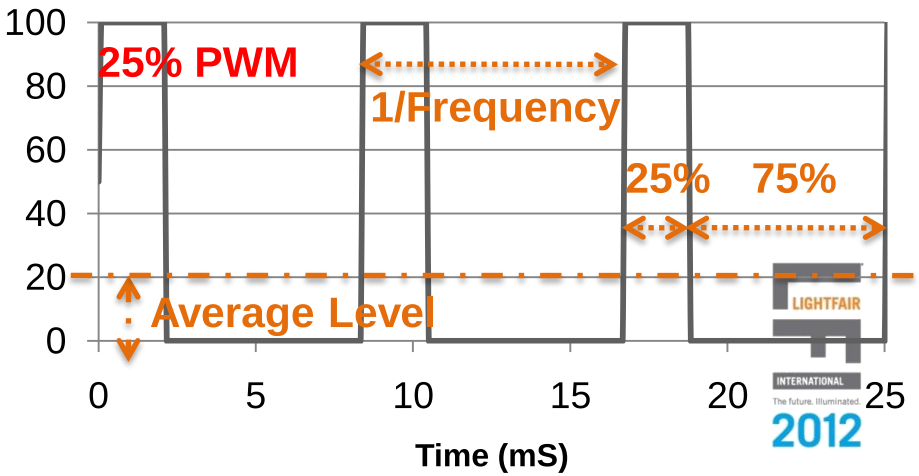
LEDs ARE easy to dim!

Pulse Width Modulation (PWM)

- Same LED current, varying LED on/off (typically) times
- Longer LED lifetime
  - Less LED on time, lower temperature
- Good dimming regulation at deep dimming (same current) levels
- No color shift?
- Potential noise generation
- PWM frequency is important
  - Potentially undesirable flicker
  - Minimum dimming level





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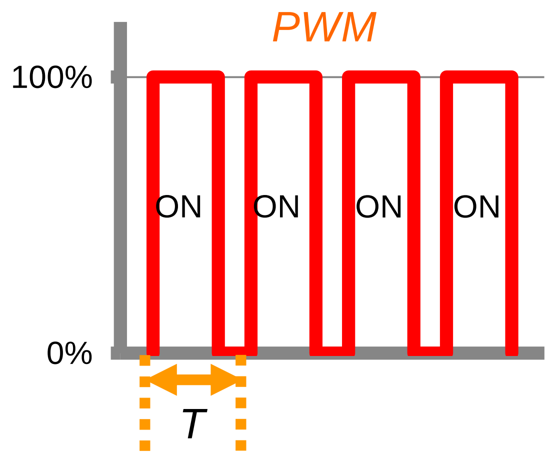
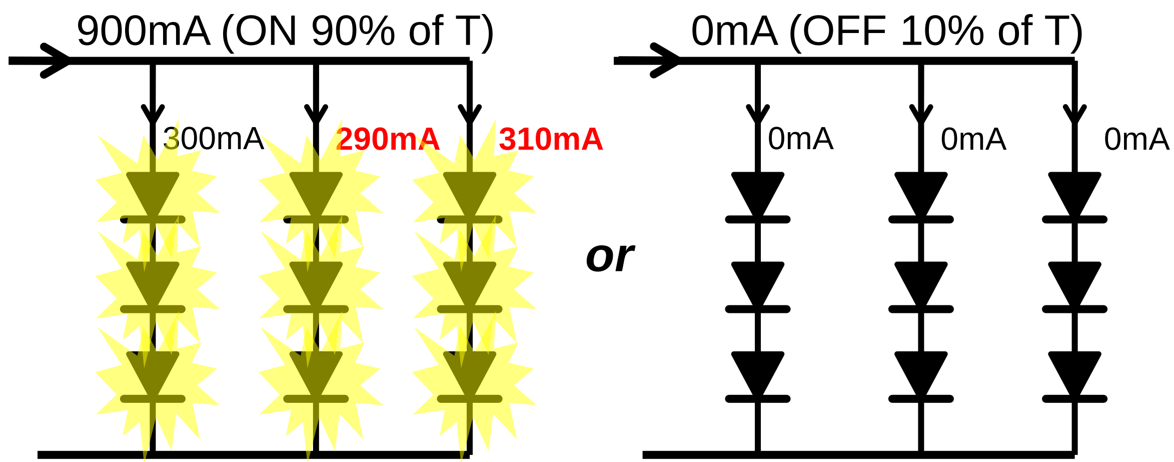
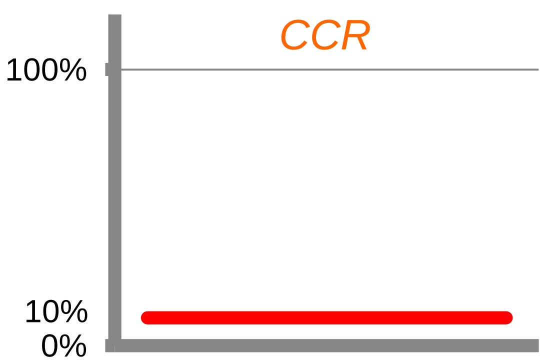
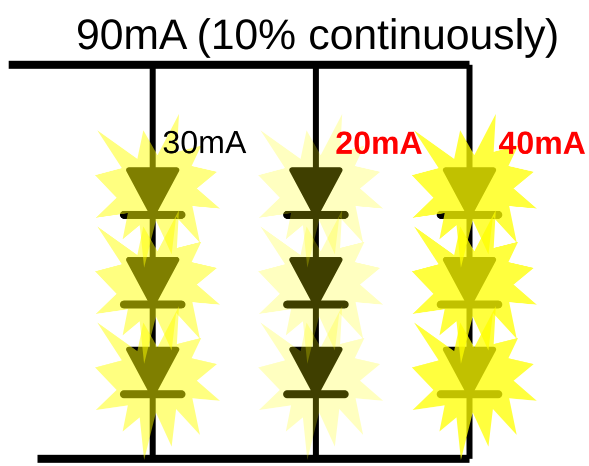
PWM vs. CCR LED architecture impacts









Slight current imbalance is very noticeable at low current levels

“Yes, it’s dimmable!”

What it says	What it might mean
1. Dimmable	1. You can do something to reduce the light output
2. Dimmable with most dimmers	2. Some of the dimmers we have in the lab reduce the light output
3. Dimmable with standard dimmers	3. Some of the dimmers we bought at the local big-box store reduce light output
4. Dimmable from 100-0%	4. The light output drops out below 10%
5. Flicker-free	5. My boss can’t see any flicker

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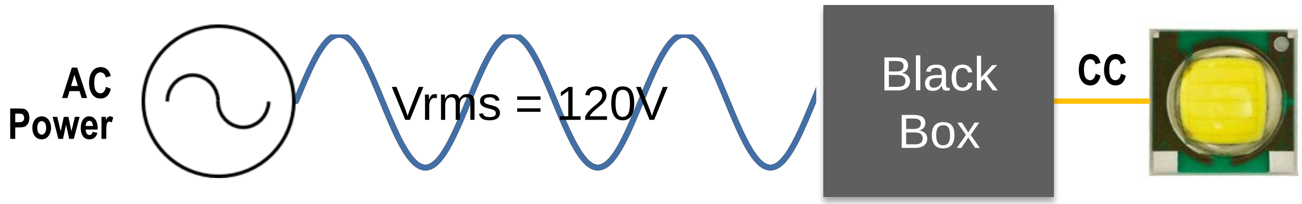
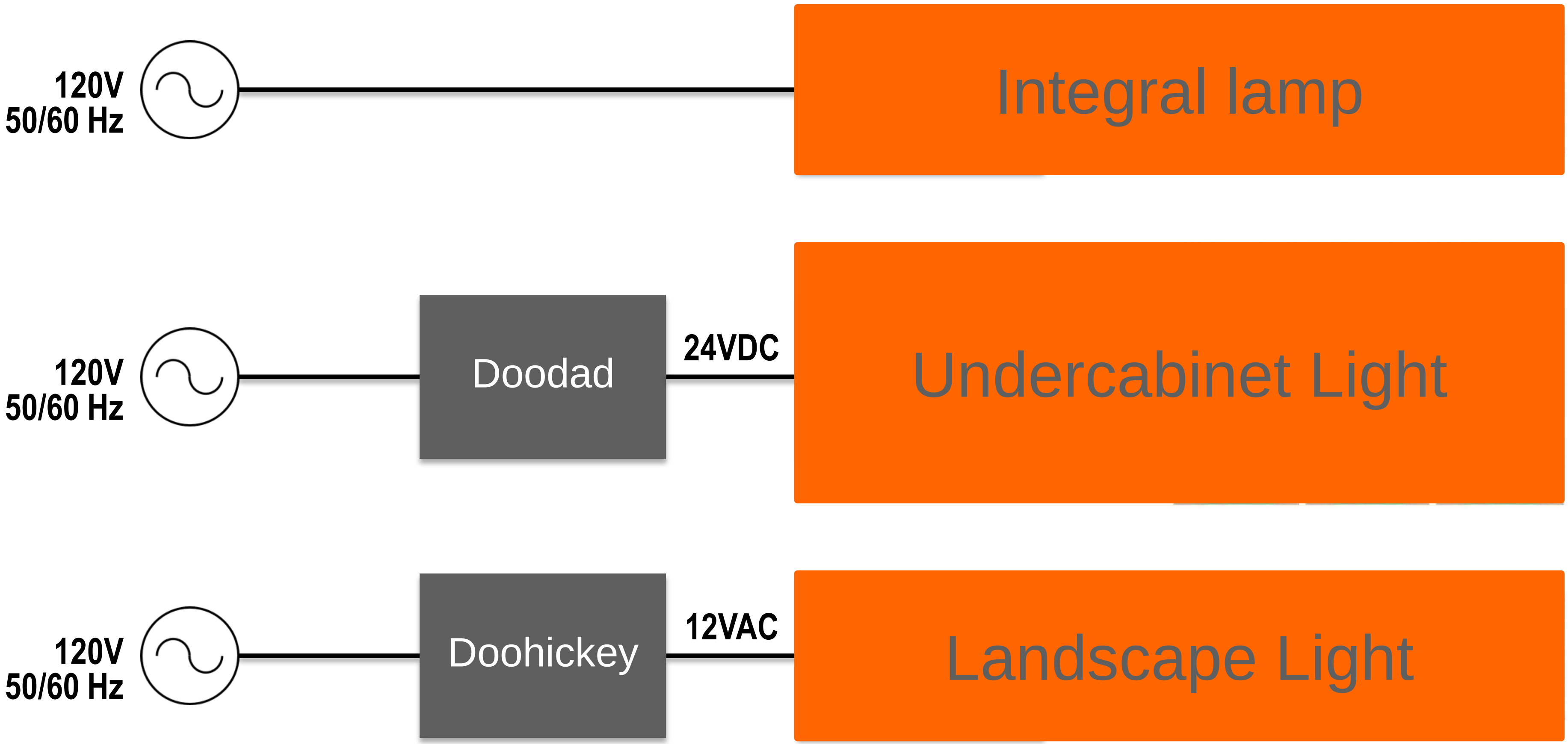
LEDs (typically) need a Driver



- Non-linear I_{led} vs. V_{led} relationship, together with manufacturing variation in V_f, mean LEDs are best regulated by controlling their current
- Typically, LEDs are operated (or "Driven") such that their (average) current is constant (Constant Current)
- Typically, power electronics components are used to create circuits which convert AC voltage into regulated LED constant (average) current

Some examples of LED system variation

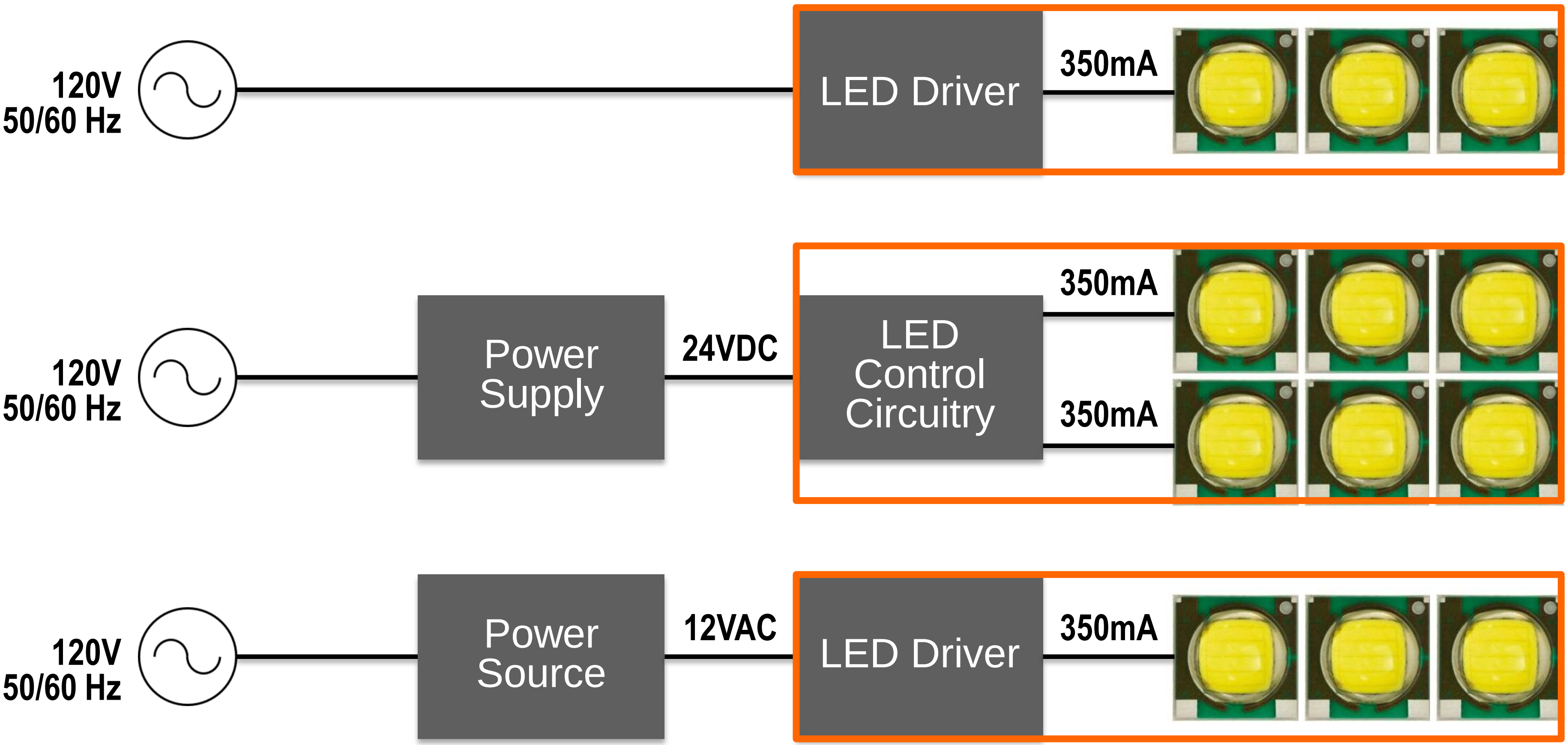


Standard terminology?

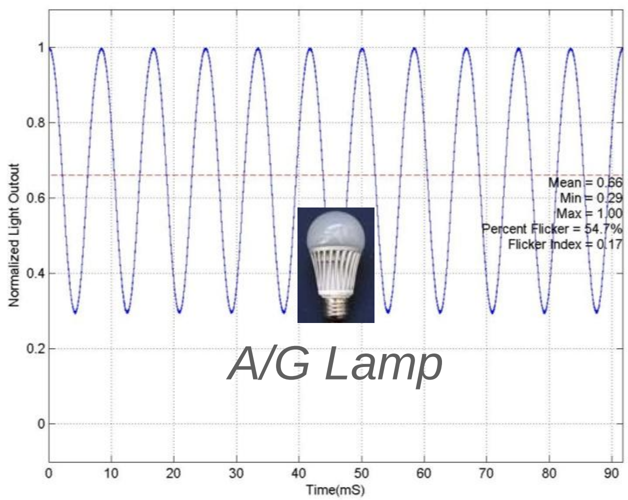
IES RP-16-10 (simplified)

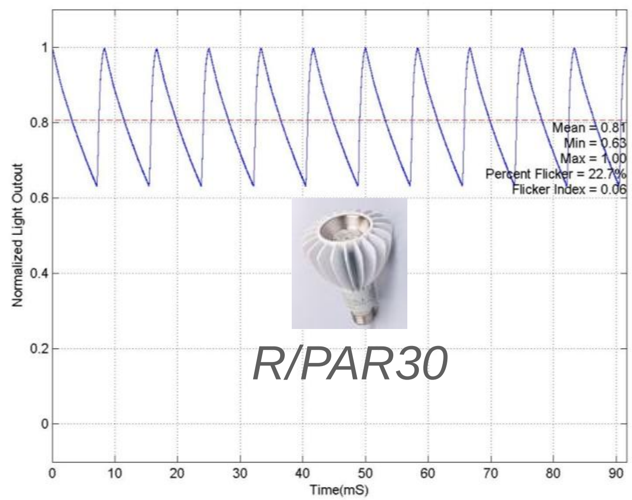
- Power source
  - Providing current, voltage, or power
  - No additional control capabilities
- Power supply
  - Providing and controlling current, voltage, or power
- LED control circuitry
  - Control a power source
  - Does not include a power source
  - Control … the electrical energy delivered to a LED
- LED driver
  - Comprised of a power source and led control circuitry

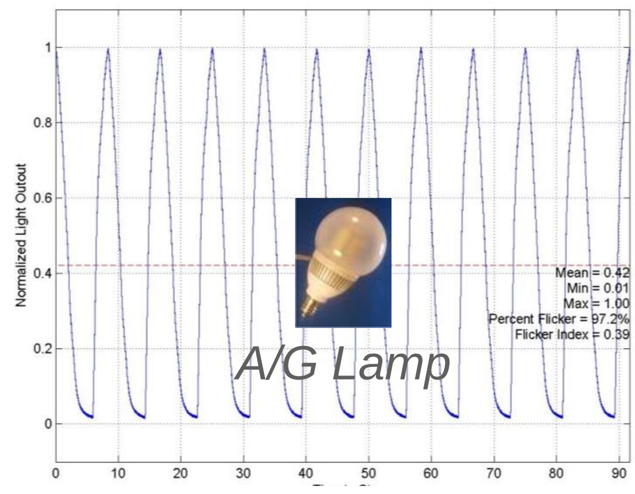
Some (clearer?) examples of LED system variation

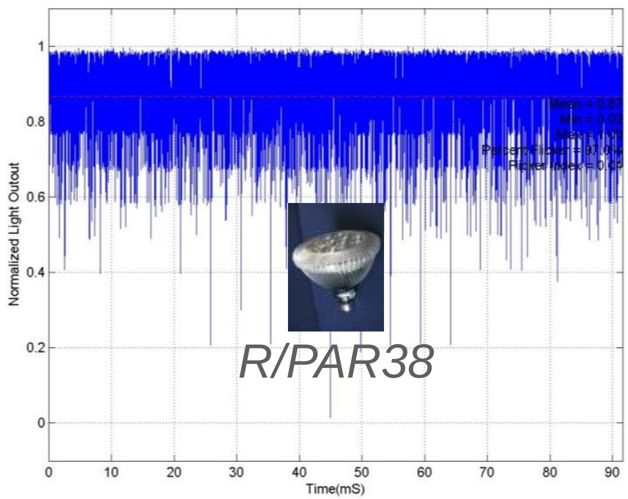


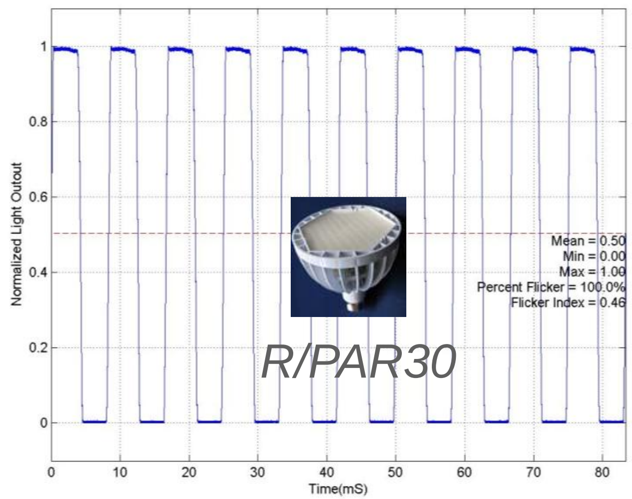
Some examples of LED flicker

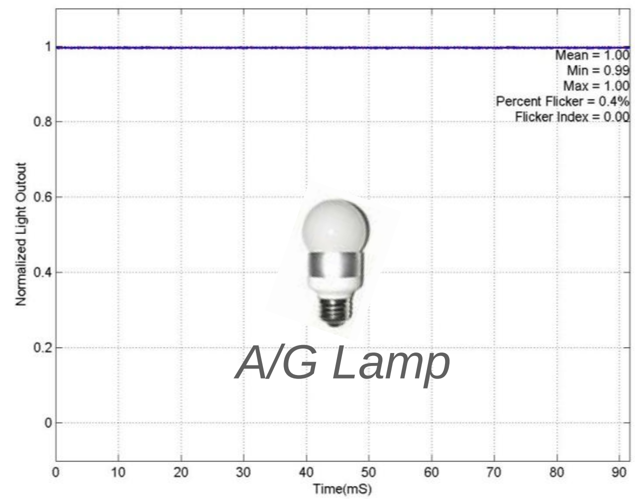












Here is where the fun begins

Q: What happens when you pair new world lighting technologies (specifically LEDs) with old world dimming technologies (specifically phase-control)?

+

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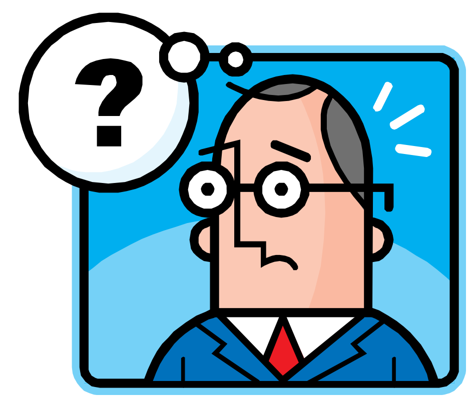
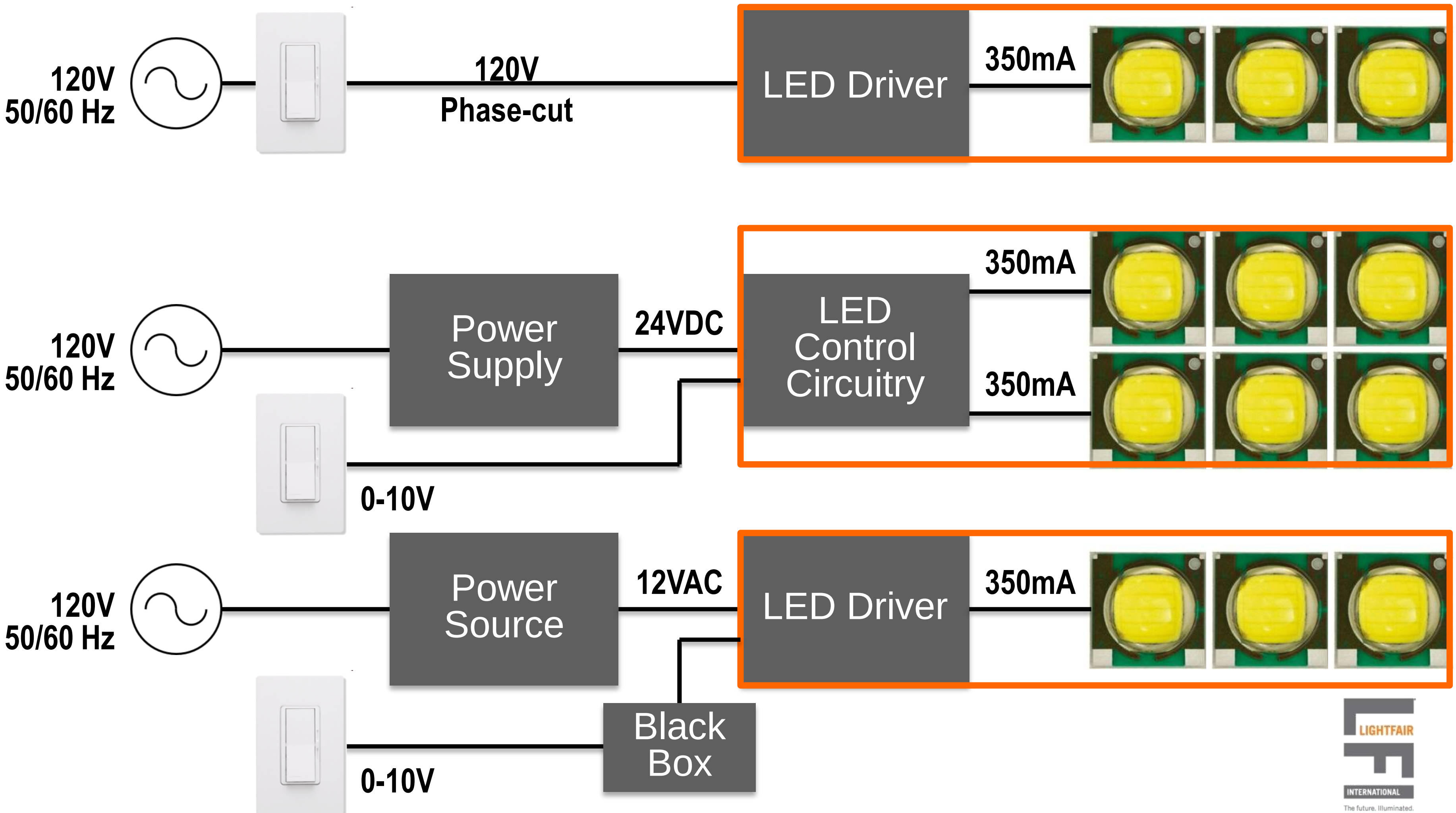


Some examples of dimmed LED system variation



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Adventures in LED lamp, phase-cut dimmer matchmaking

- CALiPER Reference: 07-09A
- Category: R30 integral lamp
- LEDs: 3 packages, 6 LEDs per package
- Measured power (without dimmer): 9 W
- Manufacturer dimmability claim
  - Dimmable, can be used with linear-resistive dimmers
- Observations
  - Dimmed to some degree with all dimmers
  - Dimmed well with D5
  - Dimmed partially to 45-80% initial output with 4 dimmers
  - Dimmed to about 25% initial output with 5 dimmers, then shut off
  - Flickers while dimming or at full dim with 4 dimmers
  - Efficacy remained fairly constant with all except one dimmer
  - No significant color shift on any dimmer
  - THD stayed steady at 76% or increased further as dimmed
  - Power factor decreased significantly from 0.57 to around 0.2 as dimmed

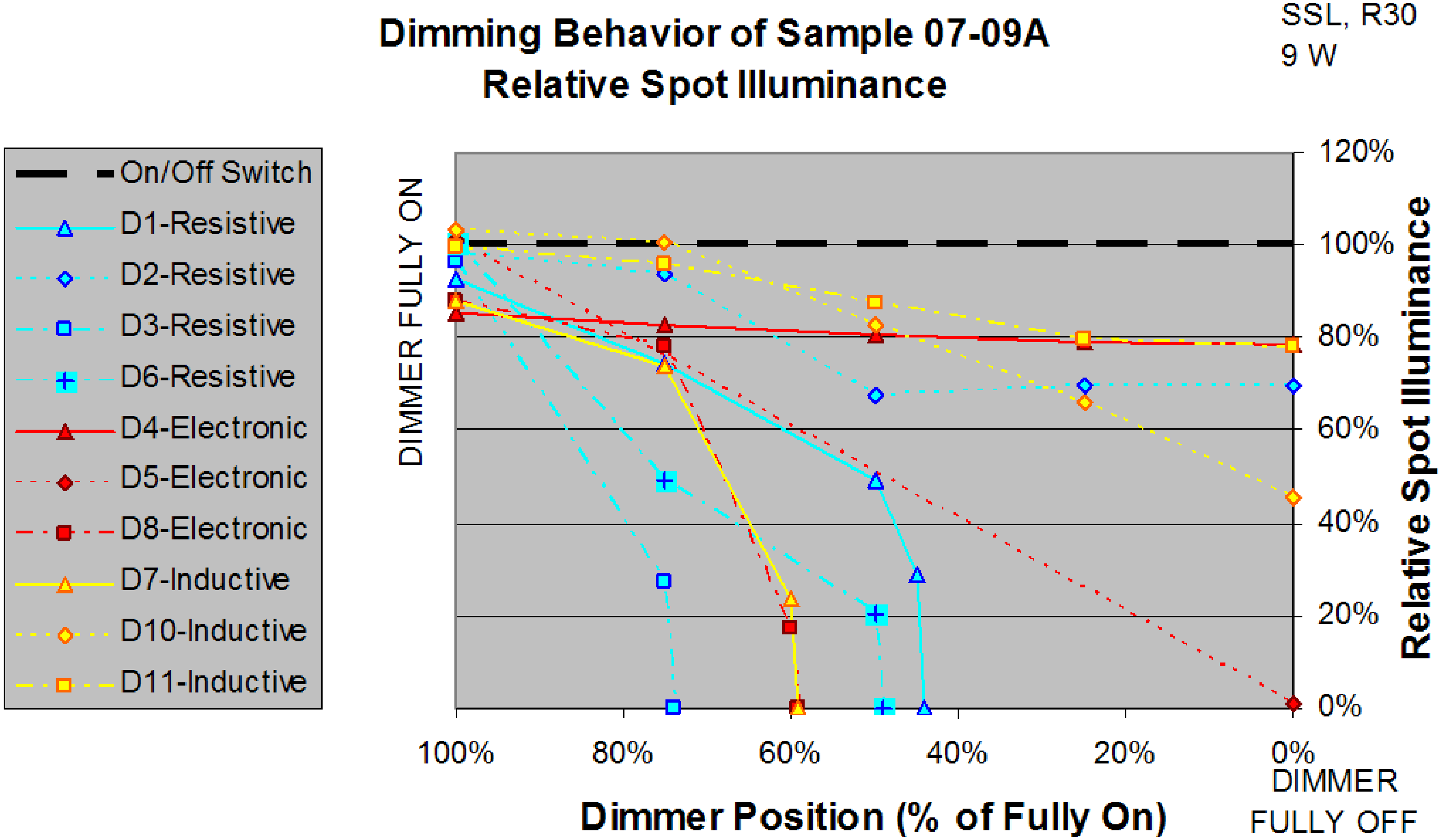
Signs of a bad date

- Upon insertion of dimmer in circuit…
  - More light, less light, no light, blown dimmer fuse
  - Power quality (THD, PF) gets worse
- As dimming is engaged…
  - No dimming, no light, continuous staircase dimming
  - Power quality (THD, PF) gets worse
- As dimming continues…
  - Dropout, dead-travel
- At any point in time…
  - Flicker, audible noise

Conclusions from multiple dates

- LED sources do not inherently shift noticeably in color as they dim
- LED sources can maintain constant efficacy or even improve efficacy as they dim
- Good LED lamp – dimmer combinations can deliver good experiences
- Bad LED lamp – dimmer combinations can deliver … almost anything
  - Poor, no dimming
  - Flicker, audible noise
  - Catastrophic failure
- Product dimming claims are unreliable

LED sources have very different dimming curves with different phase-cut dimmers



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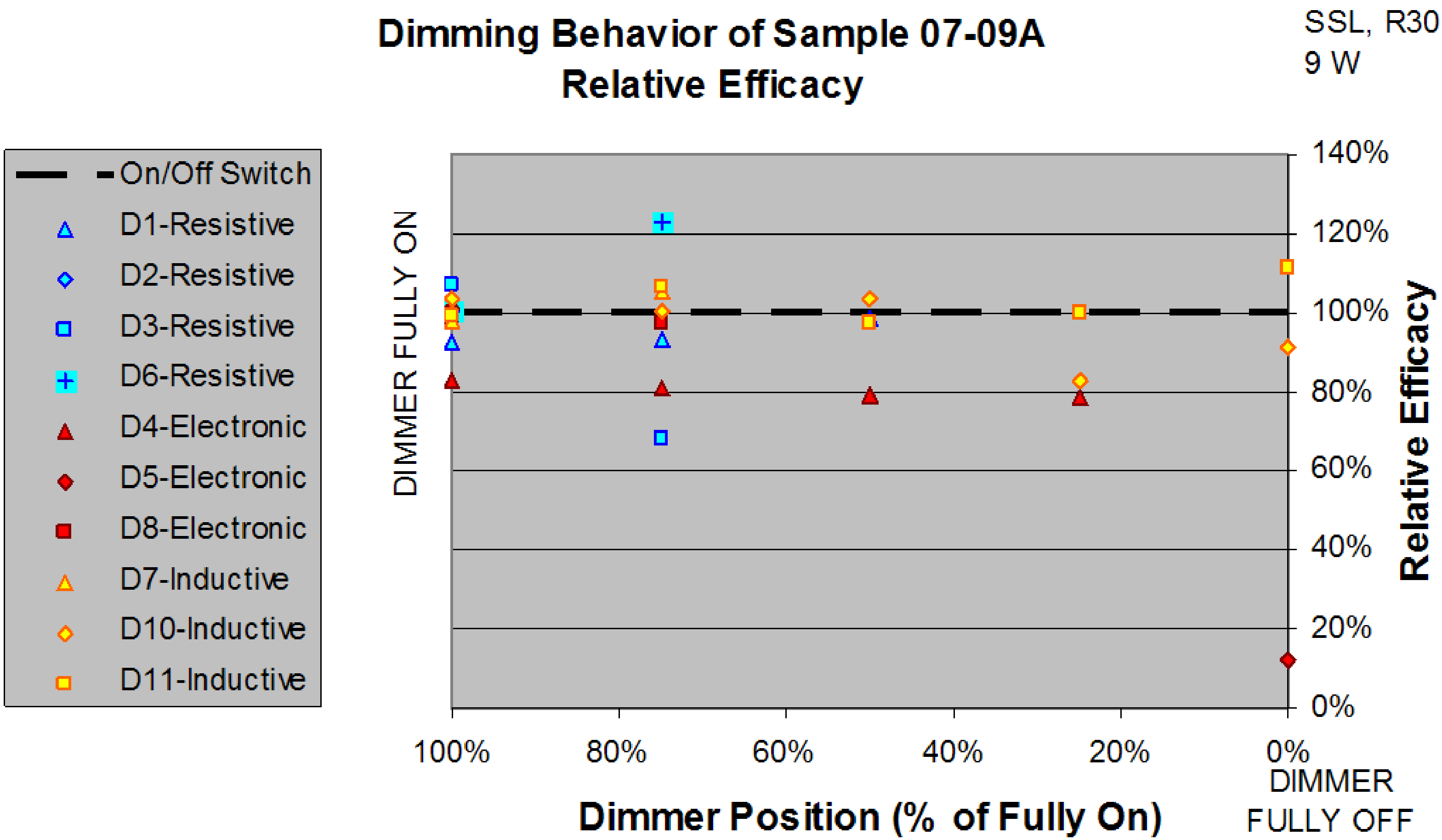
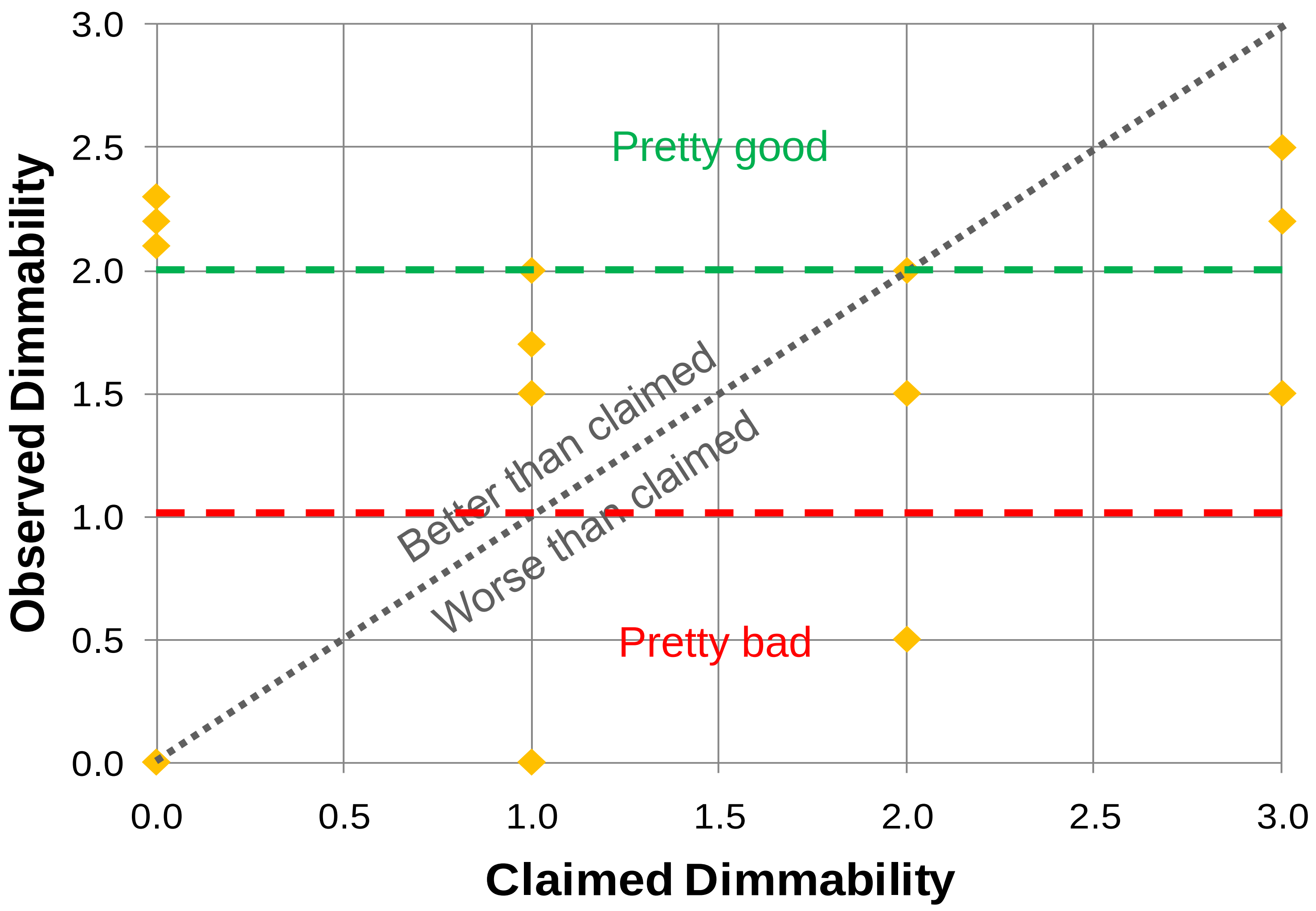
LED sources typically maintain efficacy when dimmed



Average behavior of 18 LED lamps across 11 phase-cut dimmers



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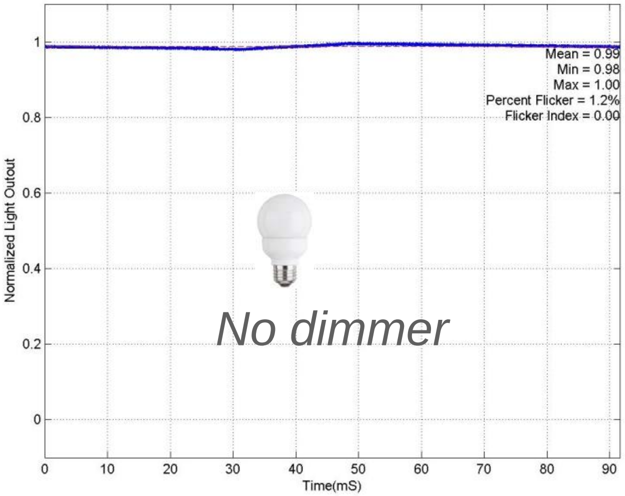
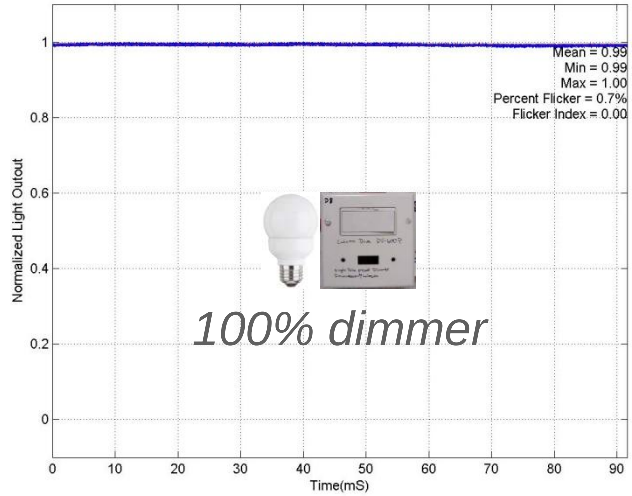
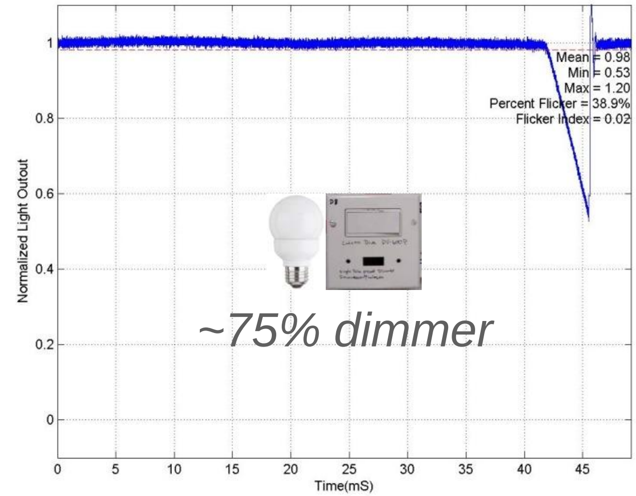
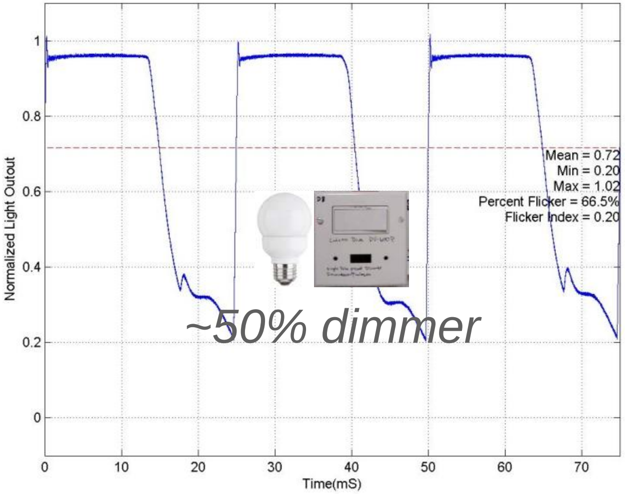
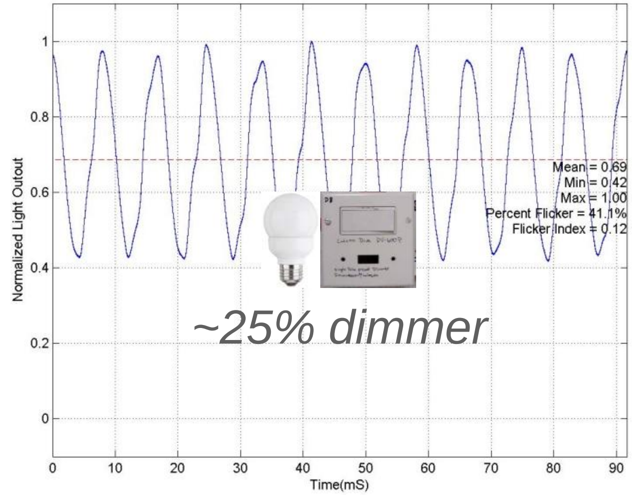
Lamp 1, Dimmer A

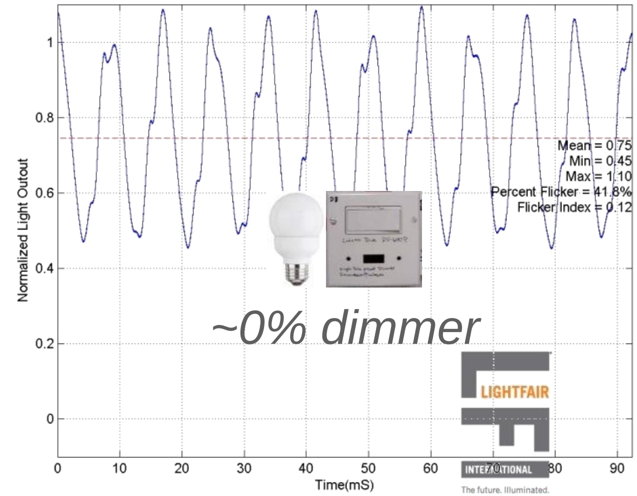












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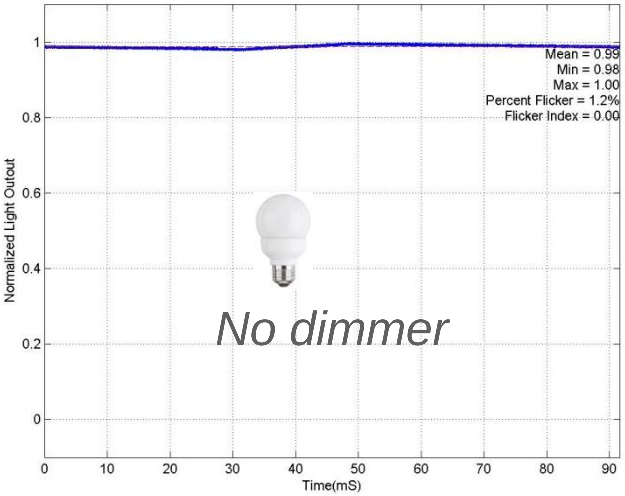
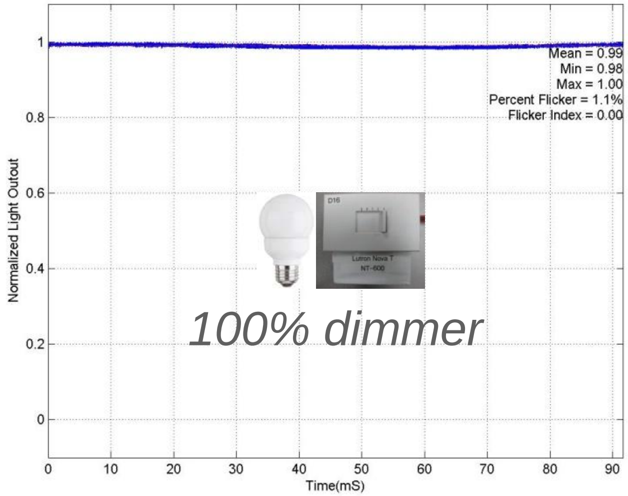
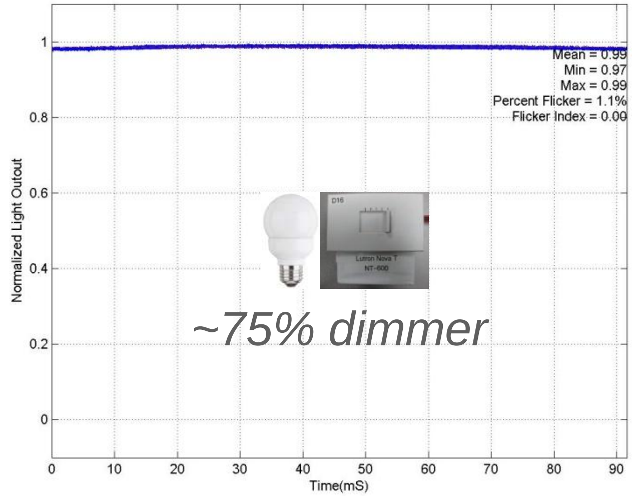
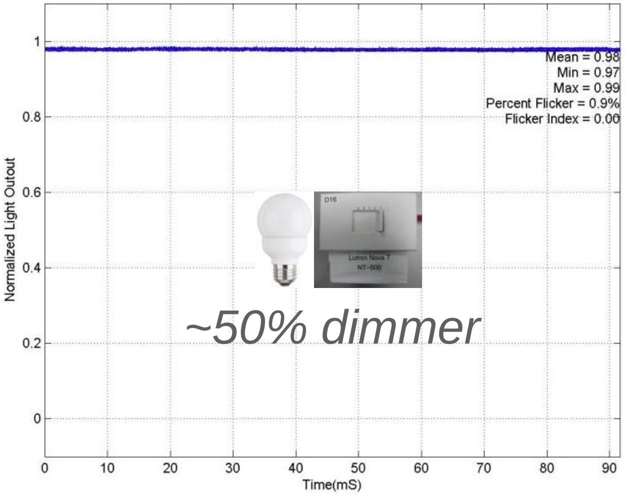
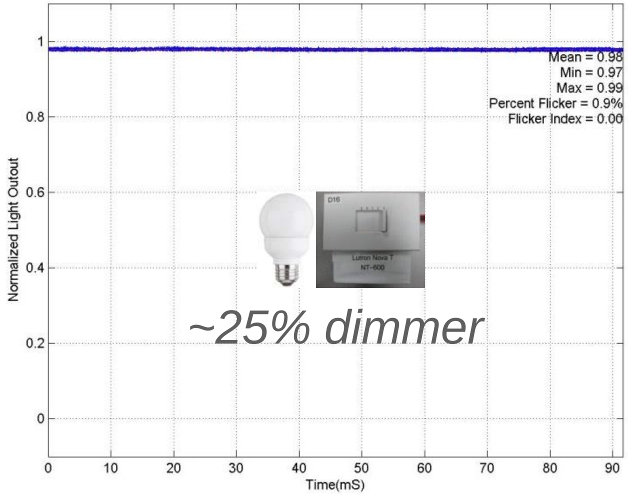
Lamp 1, Dimmer B

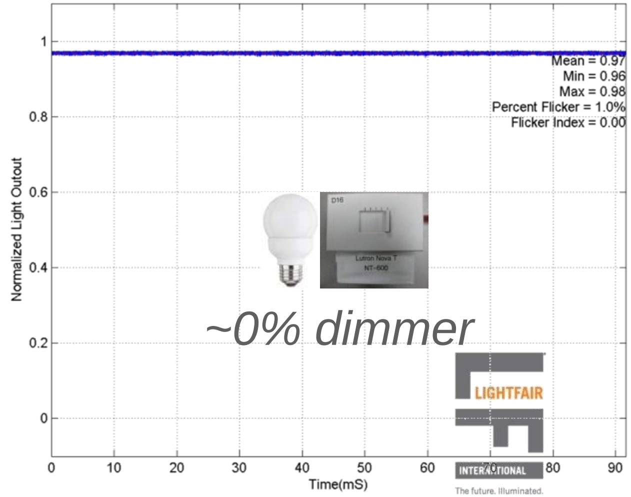




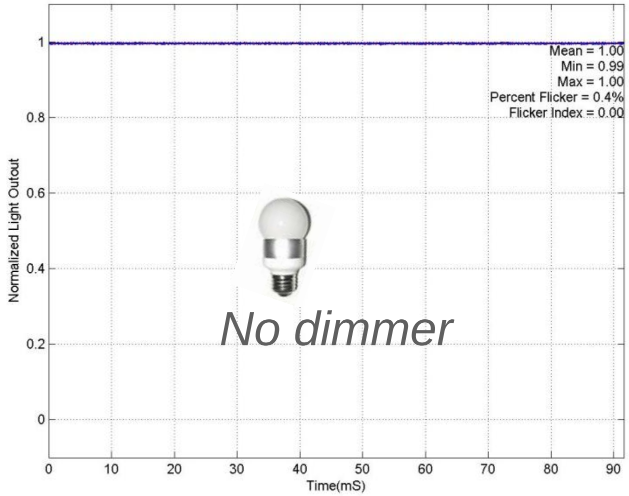


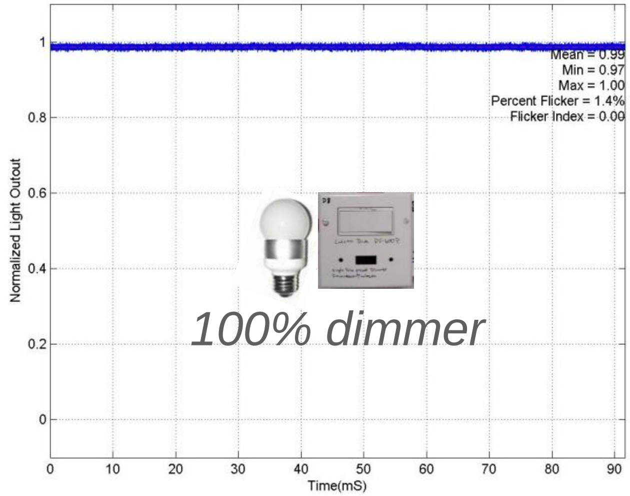


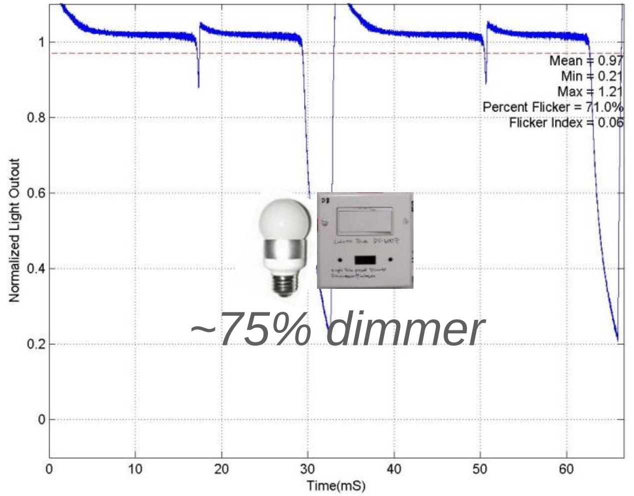


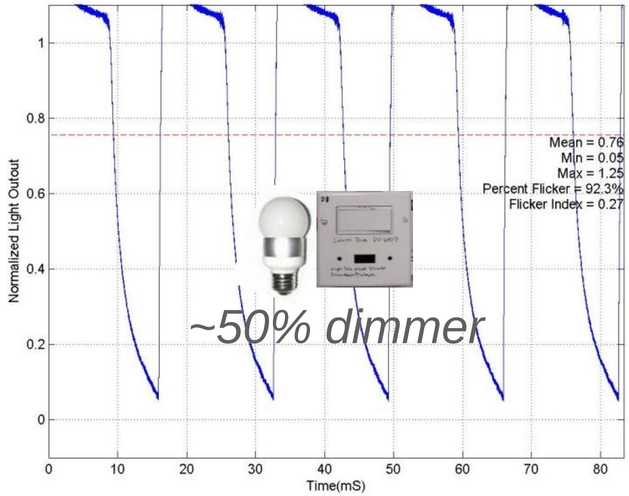


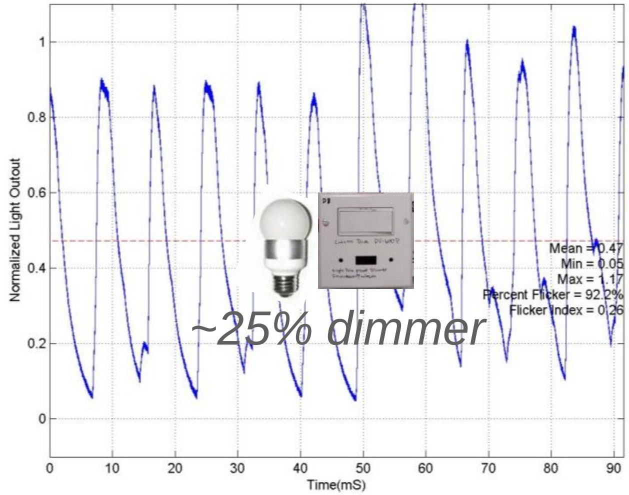
Lamp 2, Dimmer A

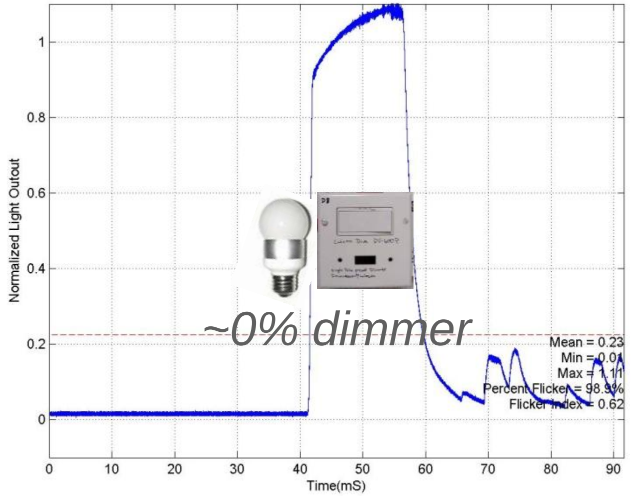




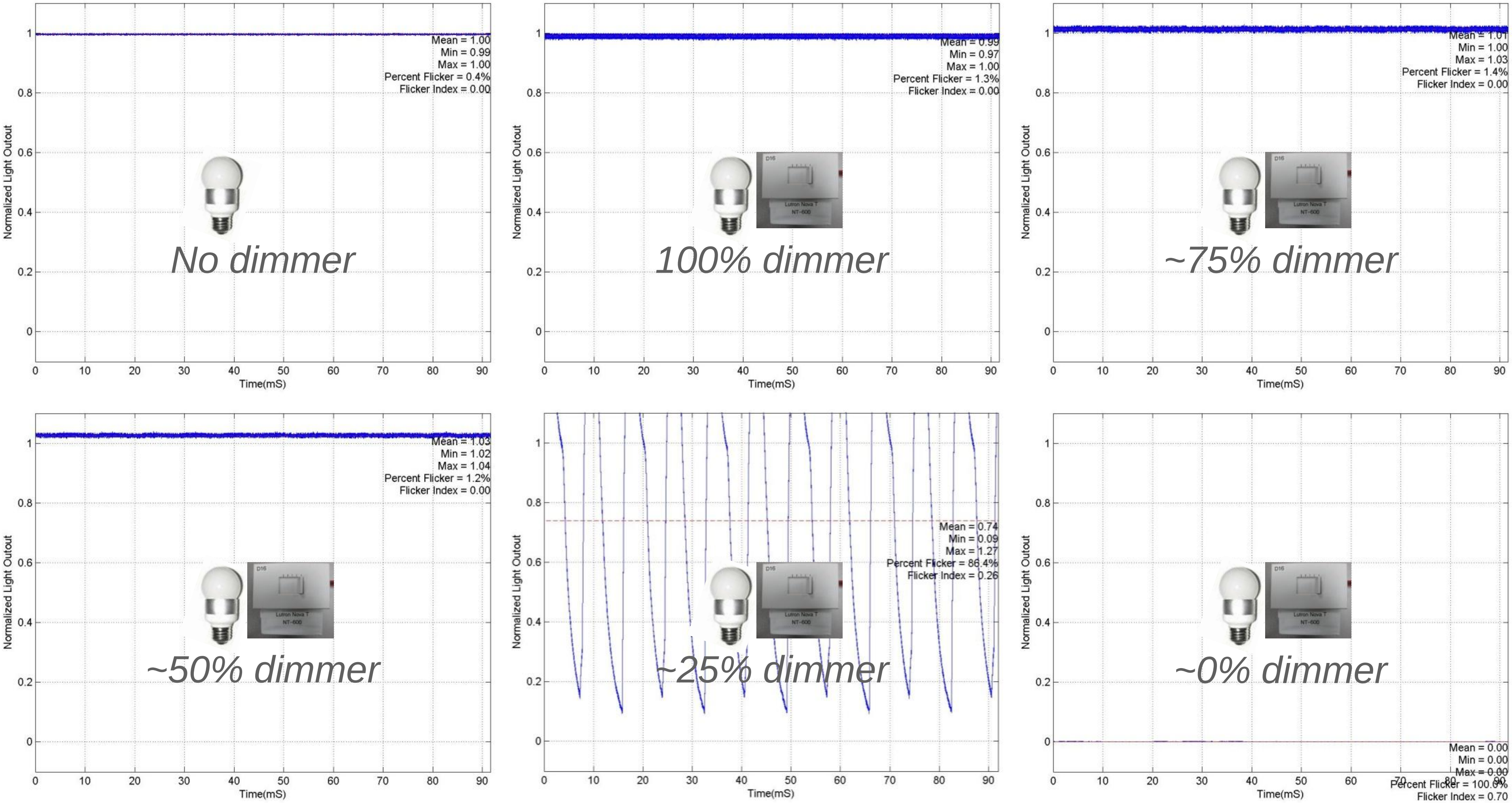




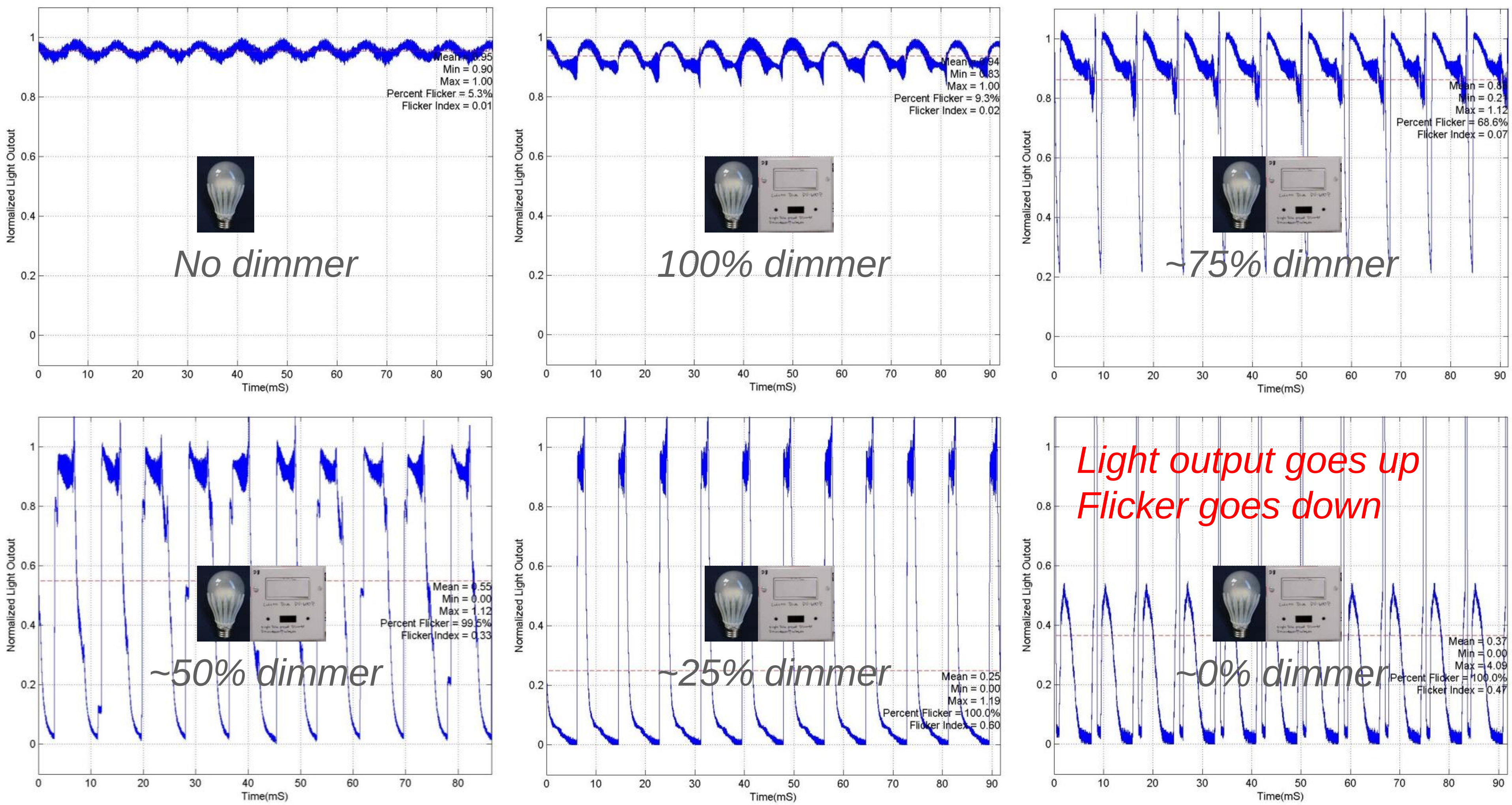




Lamp 2, Dimmer B

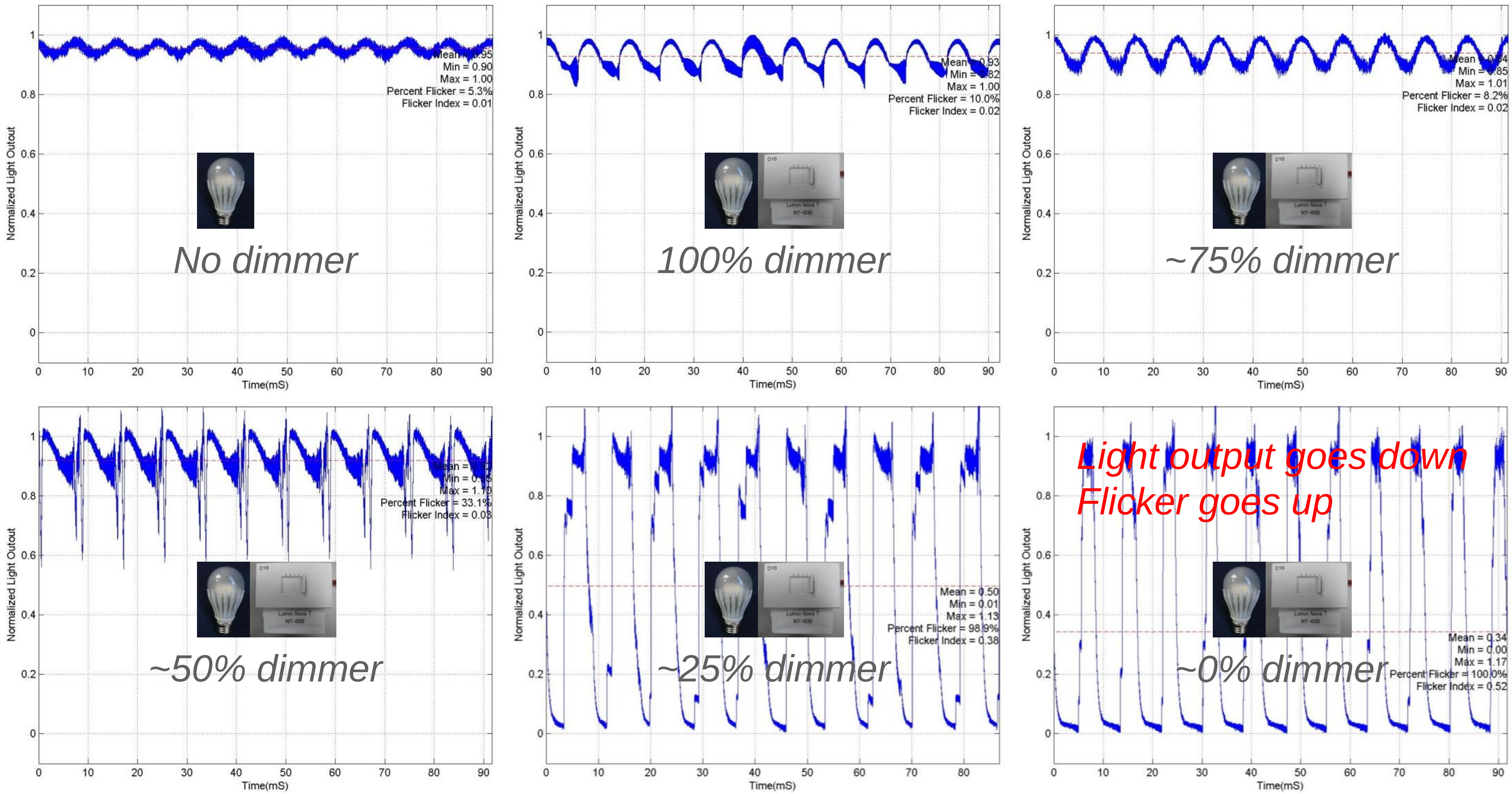


Lamp 3, Dimmer A



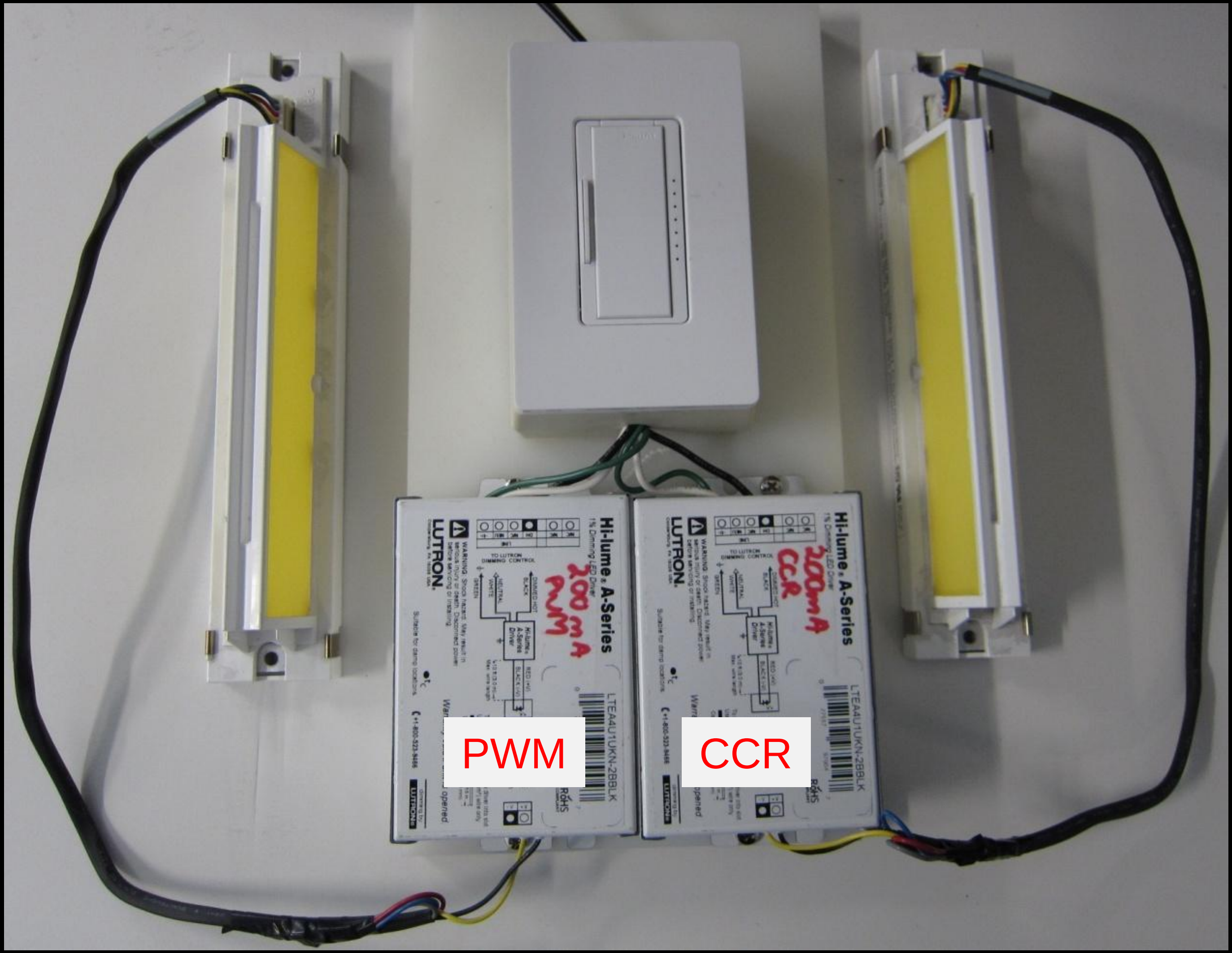
Note: PWM frequency ≈ 120Hz

Lamp 3, Dimmer B



Note: PWM frequency ≈ 120Hz

Demonstration: PWM, CCR, & flicker



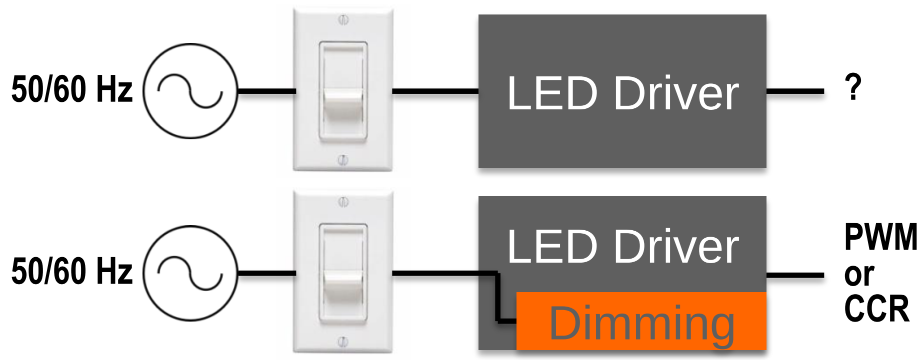
Why so much unpredictability?

- Variation in LED system architecture, driver design matter
  - LED lighting is still very much an emerging technology
  - Significant market variation today, likely for the foreseeable future
  - Lagging focus on dimmability (dimmable or designed to dim?)
- Variation in dimmer architecture, circuit design matter
  - Existing infrastructure was predominantly designed to dim incandescent sources
  - Cost, expectation barrier to replacing dimming controls
- Currently no standards for ensuring LED dimming compatibility or predictable performance
  - Standard measurement procedures or metrics for dimming compatibility or dimming performance have never existed
  - Some existing standards are not as “standard” as one would expect or desire

Two fundamentally different approaches

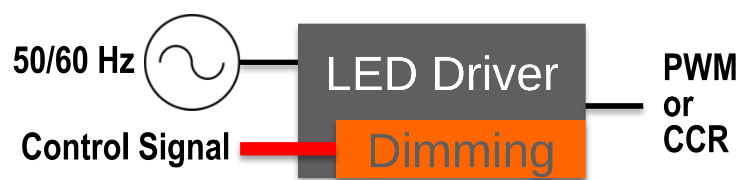
Coincident AC power and control signals

- Control signal created by AC forward or reverse phase-cutting
- Dimming performance dependent on compatibility with LED Driver
- Some LED Driver can isolate control signal by reading phase, and translating to PWM or CCR



Separate AC power and control signals

- Multiple existing standards (e.g. 0-10V, DALI)
- Control signal does not interfere with LED Driver AC power
- LED Driver implements PWM or CCR



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Old world vs. new world of dimming

Old World

- "Dimmable" typically doesn't have to be specified
  - All incandescent sources are inherently dimmable
- Dimming implies incandescent performance
  - All light sources turn on at same time/rate
  - Smooth and continuous dimming to 0.1%
  - Dim to warm
- Dimming doesn't cost extra

New World

- "Dimmable" must absolutely be specified
  - Some LED sources dim, some do not
- Dimming performance is unclear or indeterminate
  - Some light sources may have a delayed start
  - Unknown dimming curve and range
  - Unknown or no CCT shift during dimming
- Dimming adds cost to the solution

If you remember nothing else …

1. The LED driver determines dimming performance
   - Dimming range (20%, 10%, 5% …)
   - Dimming curve (linear, logarithmic, measured, perceived …)
   - Dimming smoothness
2. LED driver compatibility with the dimming control determines to what degree it can deliver upon its designed performance
   - MANY technical issues affect performance, and must be addressed (by someone)
   - Systems with separate AC power and control signals minimize some, but not all issues

Things to think about

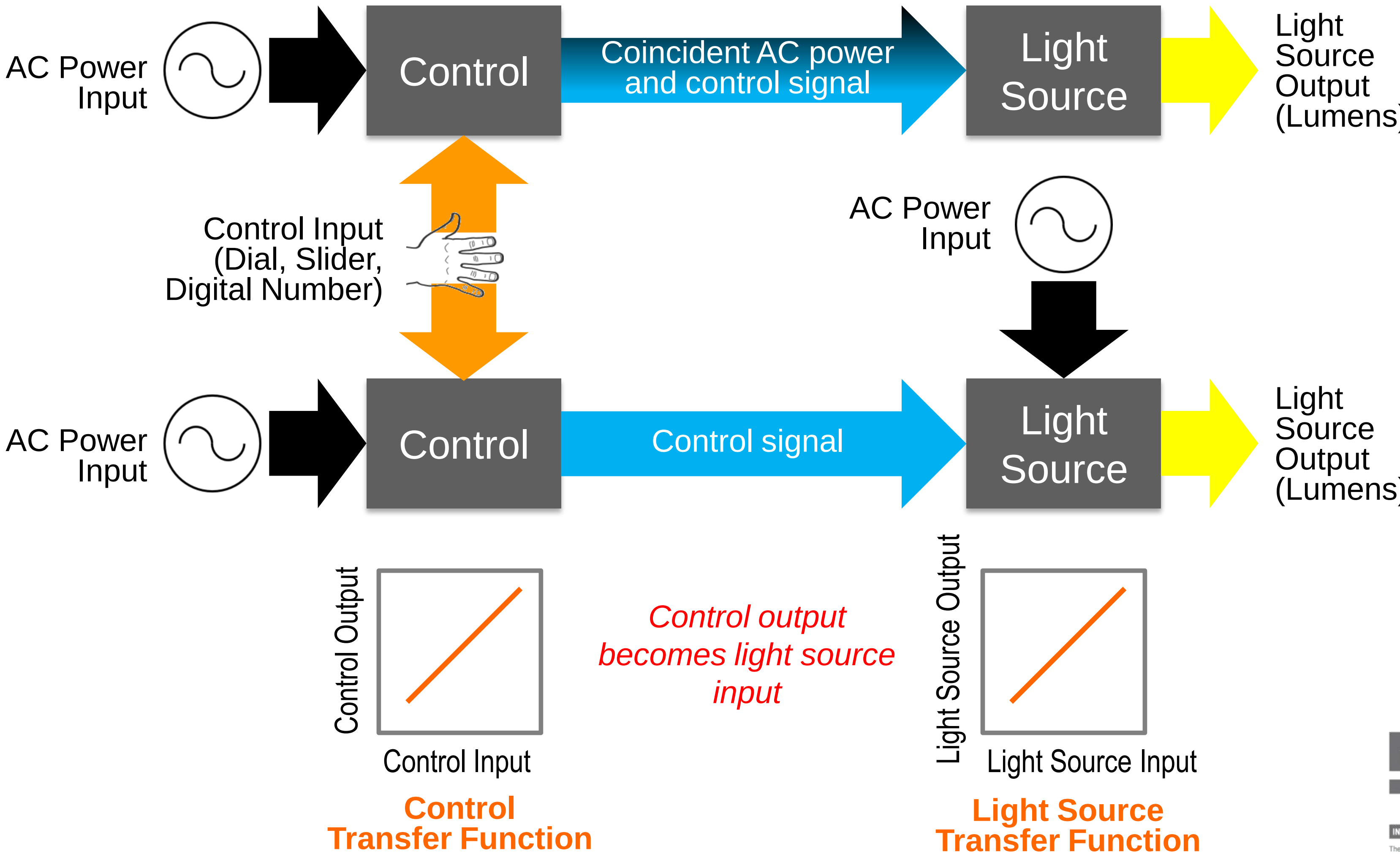
- What are your real, specific dimming requirements?
- How much control do you have over the full design to commissioning cycle of the lighting systems in your projects?
  - System: light sources, transformers, controls, wiring
  - Design to commissioning cycle: architects, lighting designers, manufacturer services, electricians, contractors
- How much do you rely on proven solutions, standards?
- What kind of pre-specification testing can you (afford to) do?
- You are going to have to learn new things; how far are you willing to go?

BREAK!

15 minutes

Next: what still needs fixing: the technical nitty-gritty

Basic lighting control block diagram



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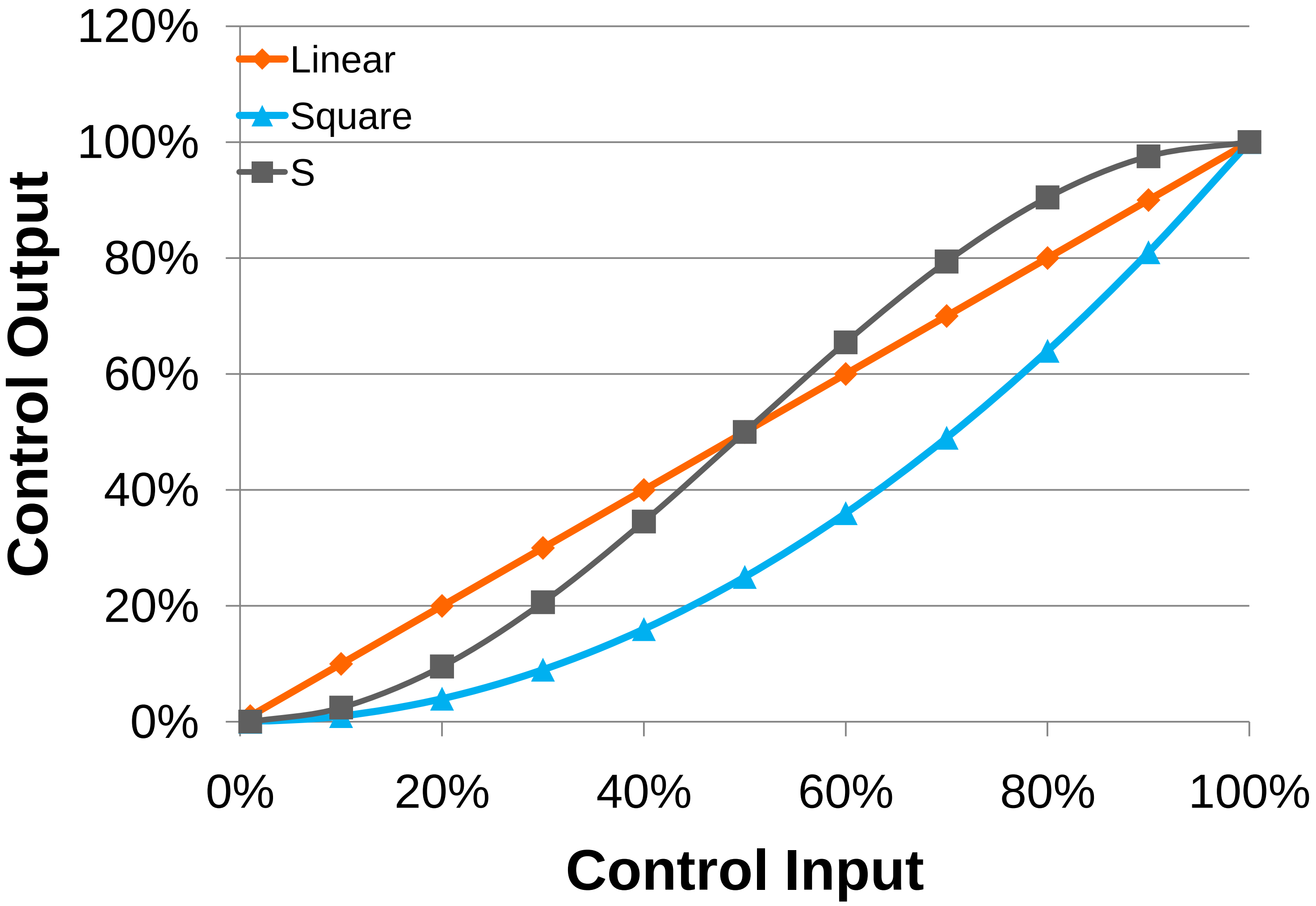
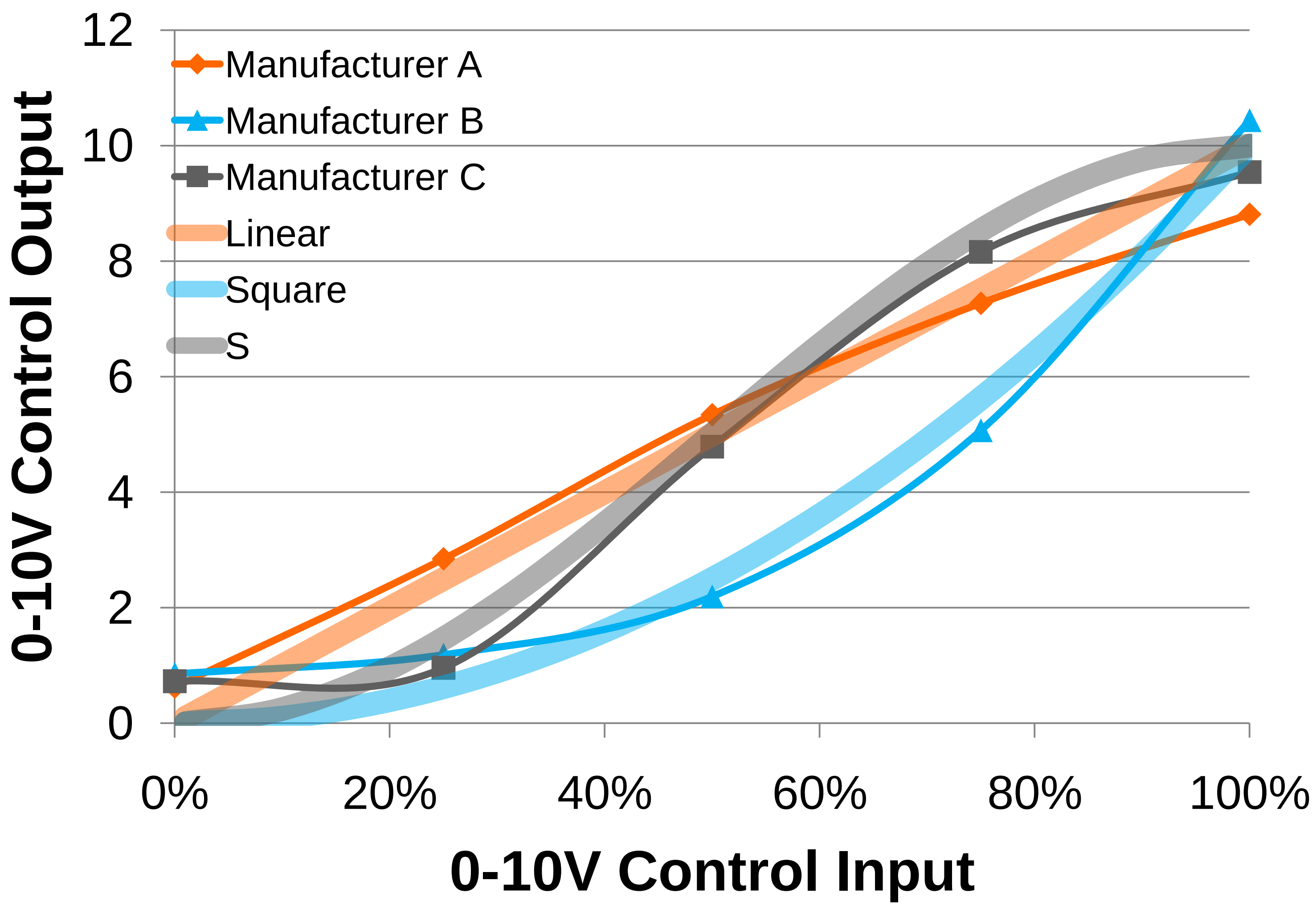
Common ideal control transfer functions



Dimmer control manufacturers target different transfer functions



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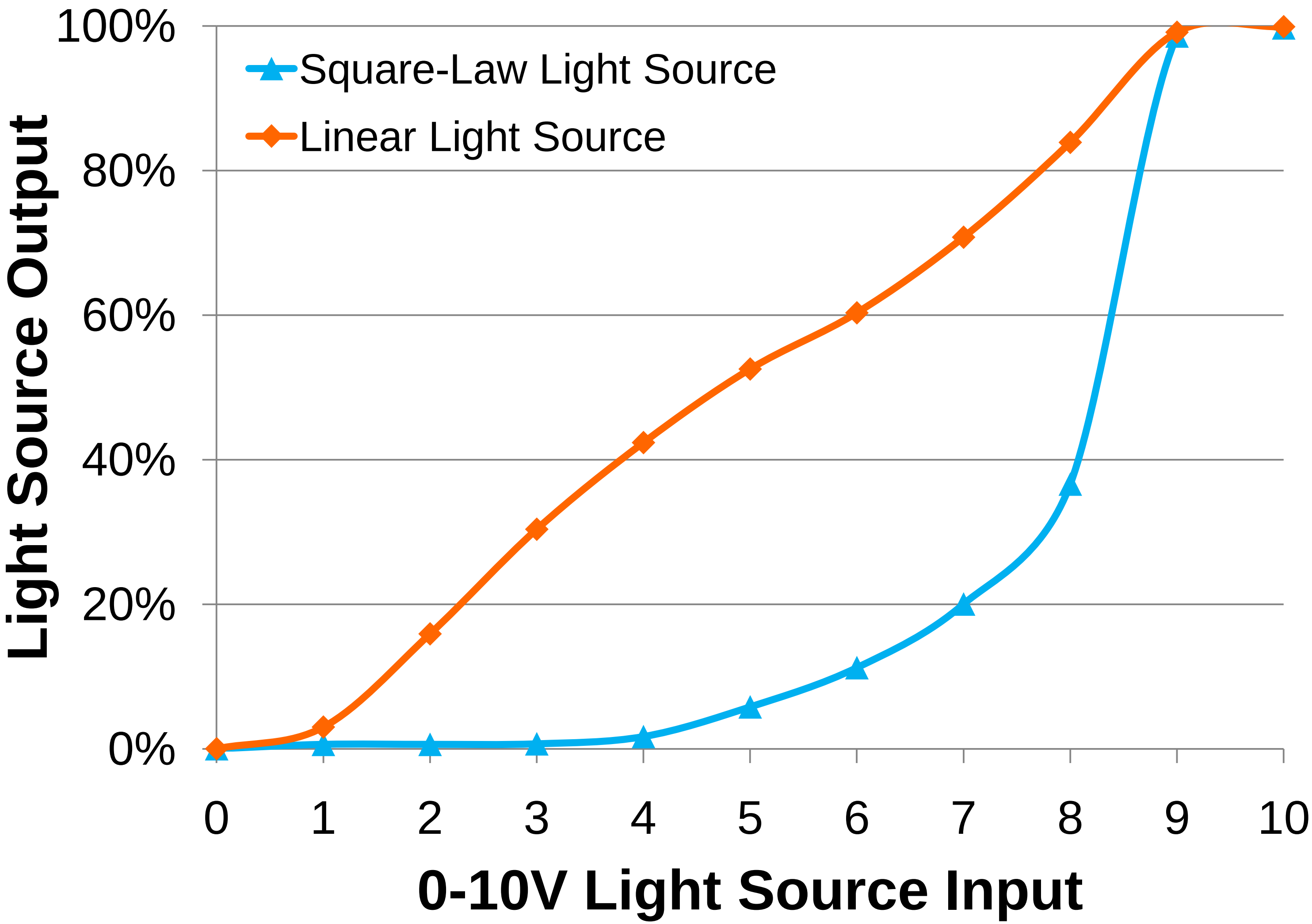
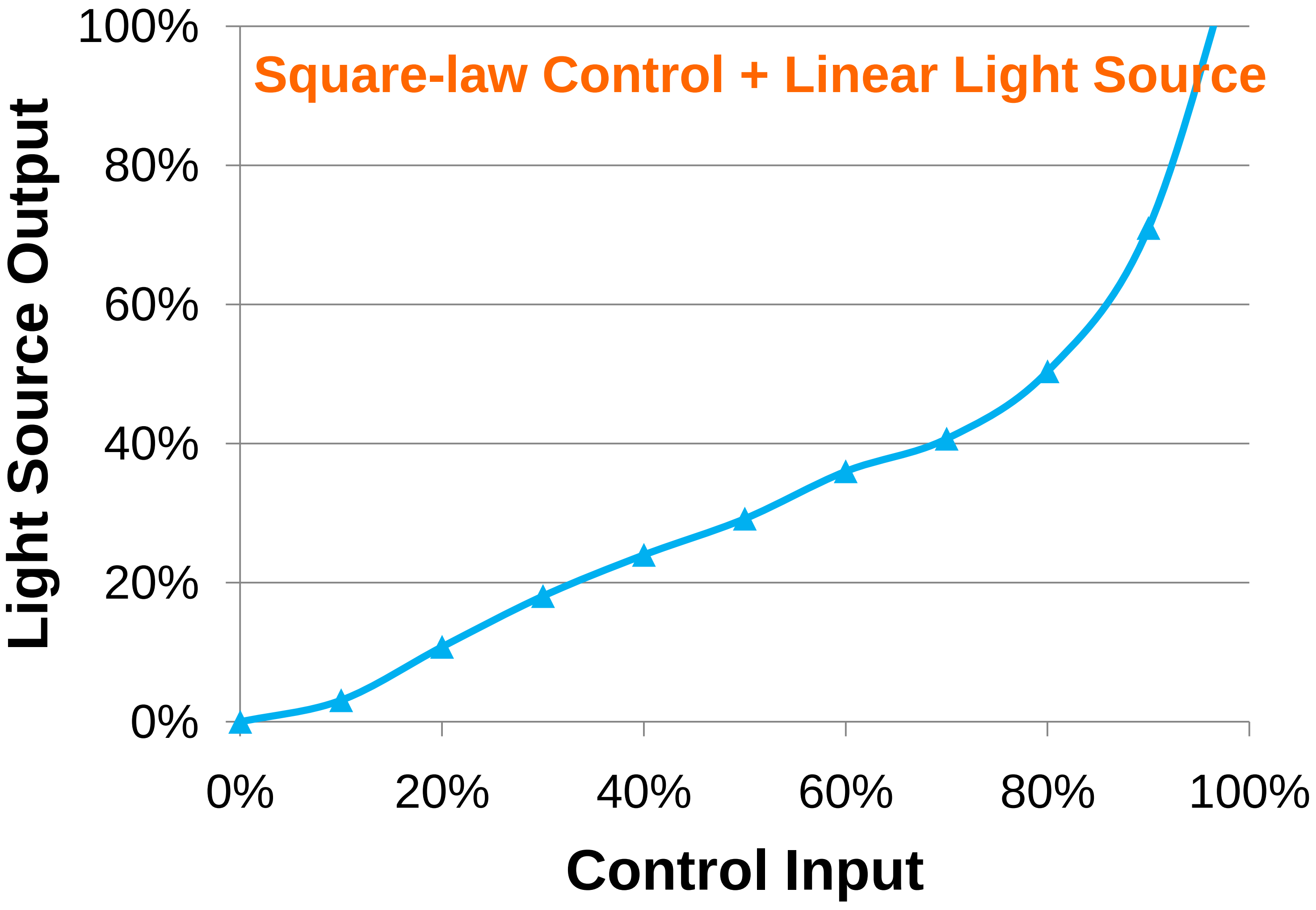
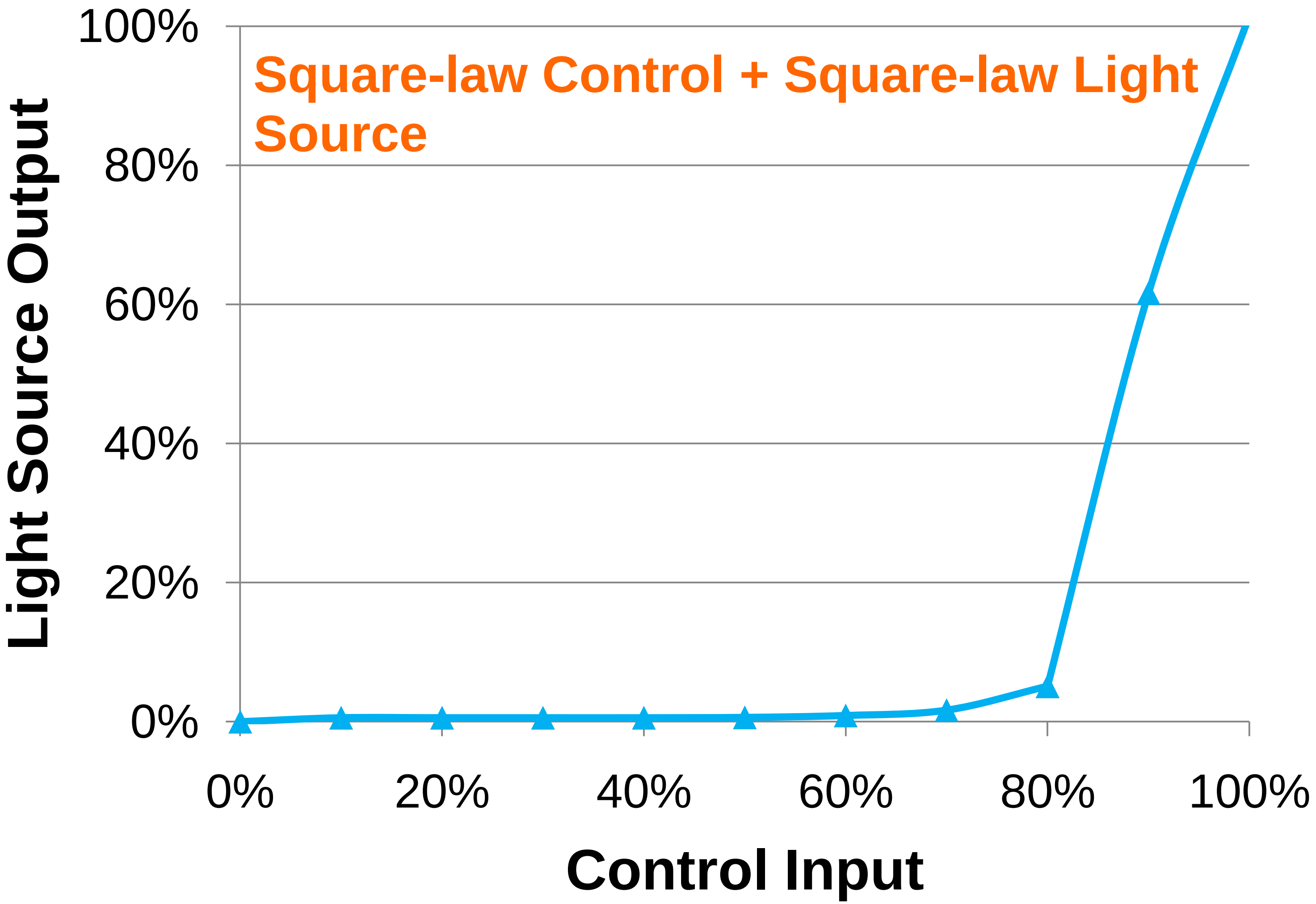
Different light source manufacturers target different transfer functions



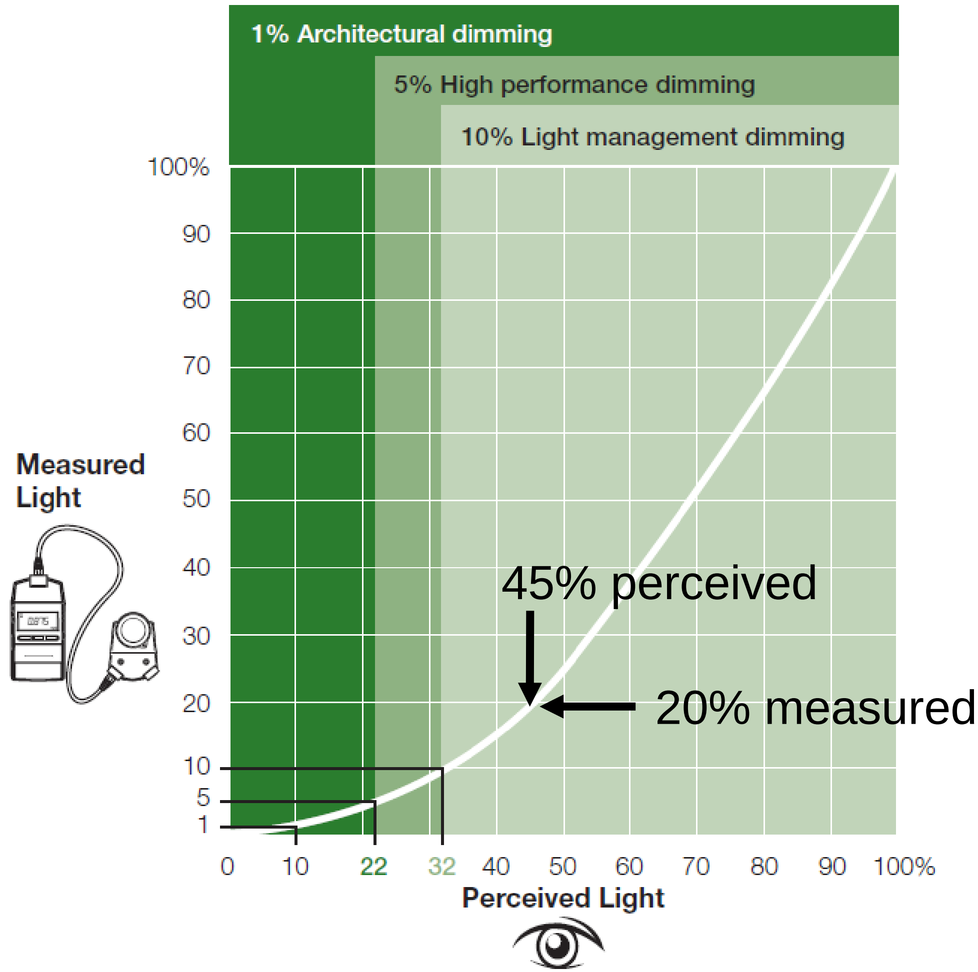
Sometimes this works



Sometimes this doesn't work



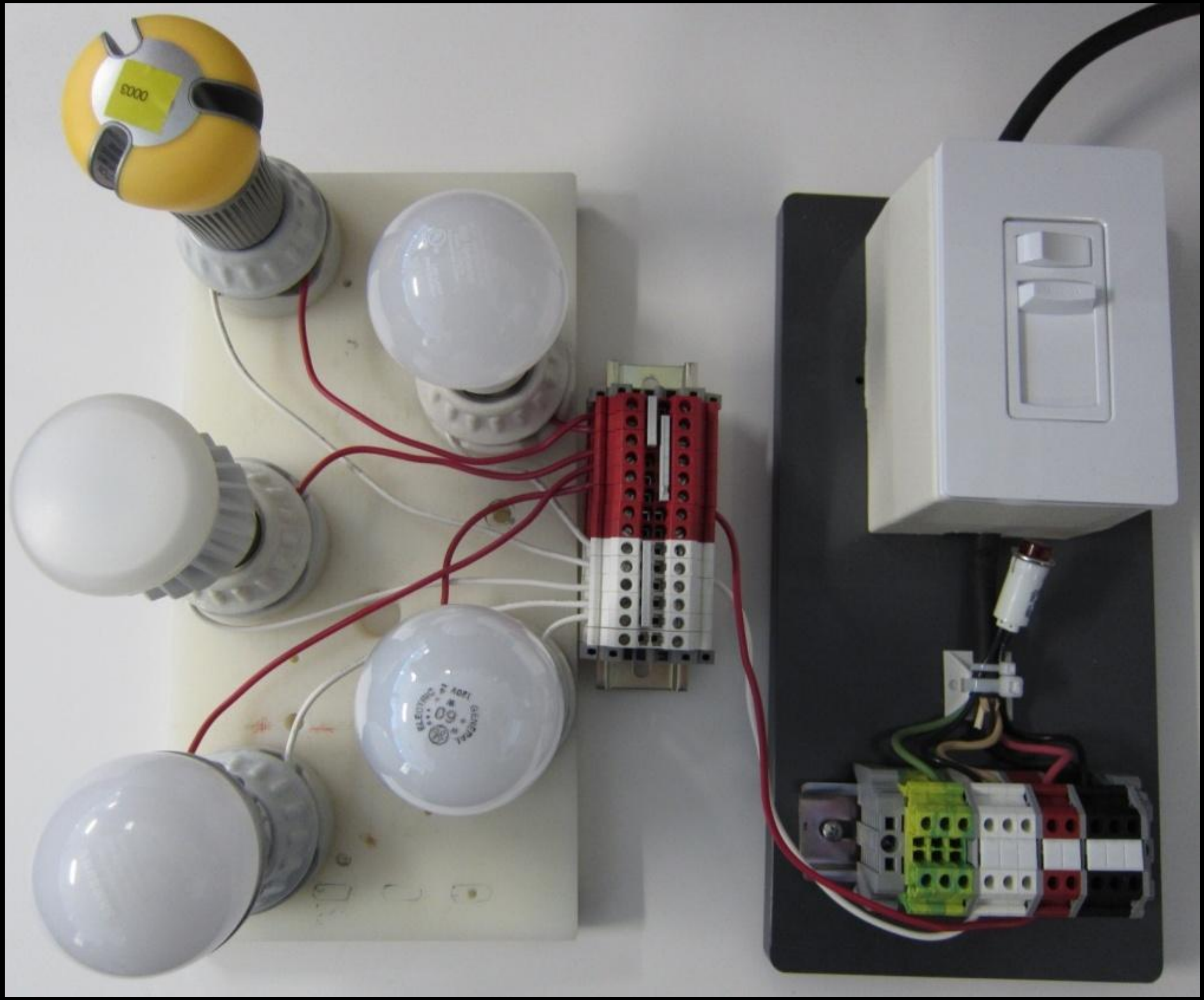
Dimming level and range



- Measured light
  - light meter reading
  - illuminance
- Perceived light
  - visual interpretation
  - affected by adaptation, eye dilation
- What does 50% dimmed mean?
  - dimmer position
  - energy consumption
  - measured light
  - perceived light

Source: IESNA Lighting Handbook, 9th Edition

Demonstration: Dimming Range & Curves



Technical details that affect phase-cut dimming performance of LED sources

- Dimmer switching element characteristics
- Dimmer standby current requirements
- Dimmer timing element characteristics
- Availability of neutral wire at the dimmer
- LED source inrush current
- LED source repetitive peak current
- LED source input RMS current
- Low-voltage system interface characteristics

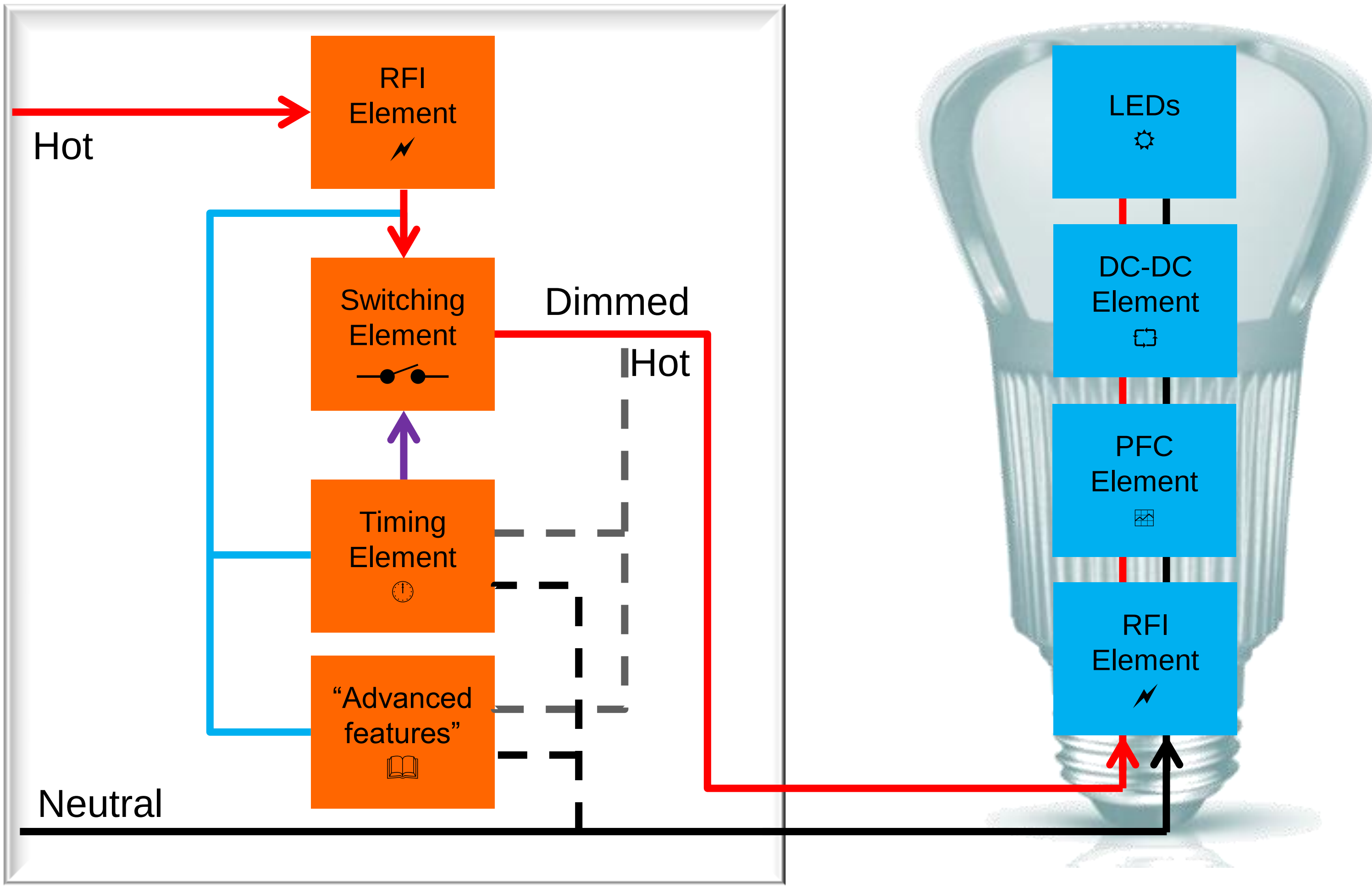
Signs of LED dimming problems

- Flicker
- Pop-on
- Drop-out
- Popcorn
- Flashing
- Ghosting
- Poor dimming curves
- Dead travel
- Audible noise
- Inoperability
- Premature failure

Dimming performance terminology

- Flashing
  - Light source is intermittently on when it should be off
- Ghosting
  - Light source is at a low-level on state when it should be off
- Pop-on
  - Dimmer setting needs to be raised above low-end level in order to get light output at turn-on
  - Light should be able to turn-on at any dimmer setting
- Drop-out
  - No light output at the bottom of the dimming range
  - The light should only turn off when the switch is turned off
- Popcorn
  - Different turn-on times for different light sources on a dimmed circuit
- Dead-travel
  - Adjusting the control without a corresponding change in light level

Anatomy of a phase-cut dimmed LED system



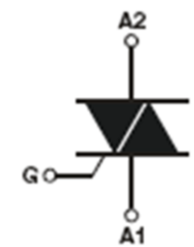
Anatomy of a phase-cut dimmed LED system

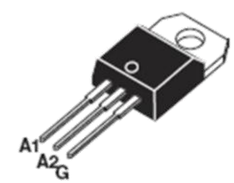
- **RFI Element**: minimizes and filters electrical “noise”, and (tries) to reduce current spikes
- **Switching Element**: the power-handling device which controls current to the load
- **Timing Element**: a circuit which determines when the Switching Element should turn on (and, in some cases, off)
- **Advanced Features**: power supply circuits needed to allow operation of internal microcontrollers, radio receivers, occupancy sensors, etc.
- **PFC Element**: Power Factor Correction
- **DC-DC Element**: Circuit which regulates current to the LEDs

Dimmer switching elements

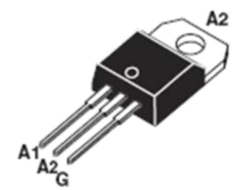
- Electronic switches
  - TRIAC (most common)
  - SCR
- The “Gate” of an electronic switch controls whether the switch is open or closed
- The Gate is actuated by an electronic signal
- A specified minimum “holding” current through the switch is required to keep some electronic switches closed

- What the #$&@! is a TRIAC anyway?





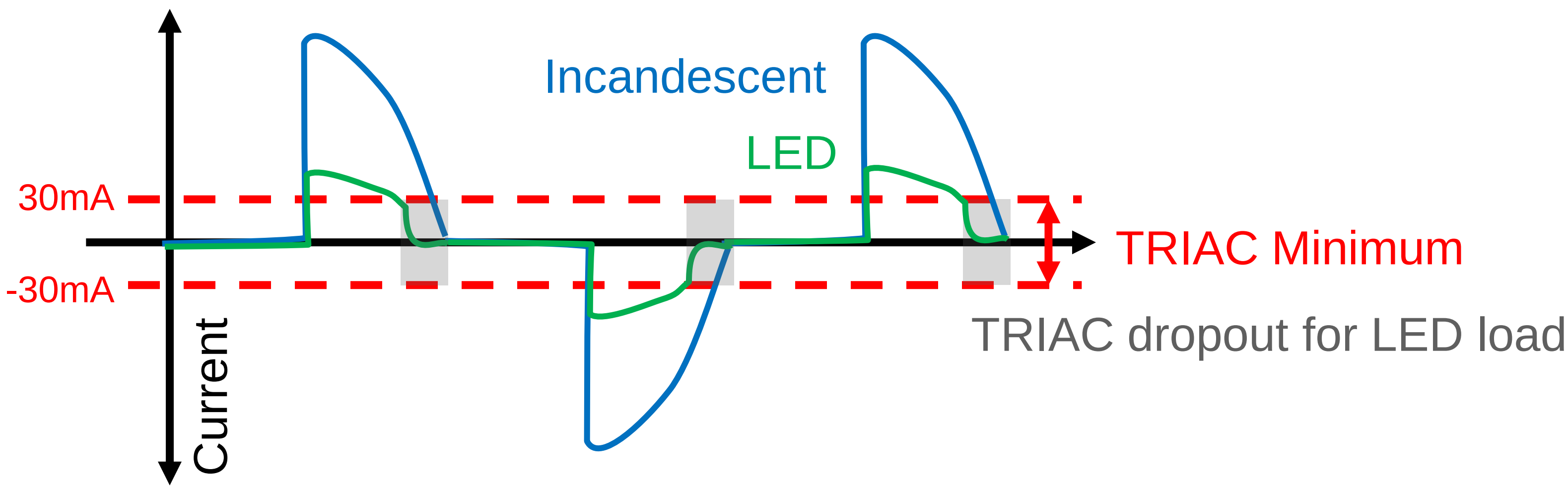
TO-220AB Insulated
(BTA10)



TO-220AB
(BTB10)

Switching Element

Minimum TRIAC current

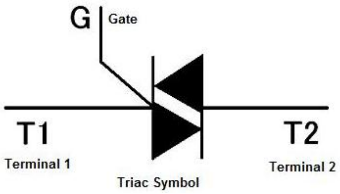


Symbol	Test Conditions	Quadrant		BTA10 / BTB10 C	BTA10 / BTB10 B	Unit
I_{GT} (1)	V_D = 12 V R_L = 33 Ω	I - II - III IV	MAX.	25 50	50 100	mA
V_{GT}	V_D = 12 V R_L = 33 Ω	ALL	MAX.	1.3		V
V_{GD}	$V_D = V_{DRM}$ R_L = 3.3 kΩ T_j = 125°C	ALL	MIN.	0.2		V
I_H (2)	I_T = 500 mA		MAX.	25	50	mA

Switching Element

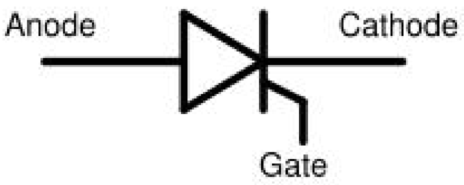
TRIACs vs. SCRs

TRIAC:



- Conducts current in both directions, allowing a single device to handle AC operation
- Single device can unintentionally latch into next half cycle
  - Sometimes a problem for LED loads
- Single device typically fails bi-directionally (open or closed in both directions)
  - No potential to harm most loads

SCR:



- Conducts current in only one direction, so two are needed for AC operation
- Device pair cannot unintentionally latch into next half cycle
- Single SCR failure results in uni-directional device pair (open or closed in one direction only)
  - Will harm magnetic loads

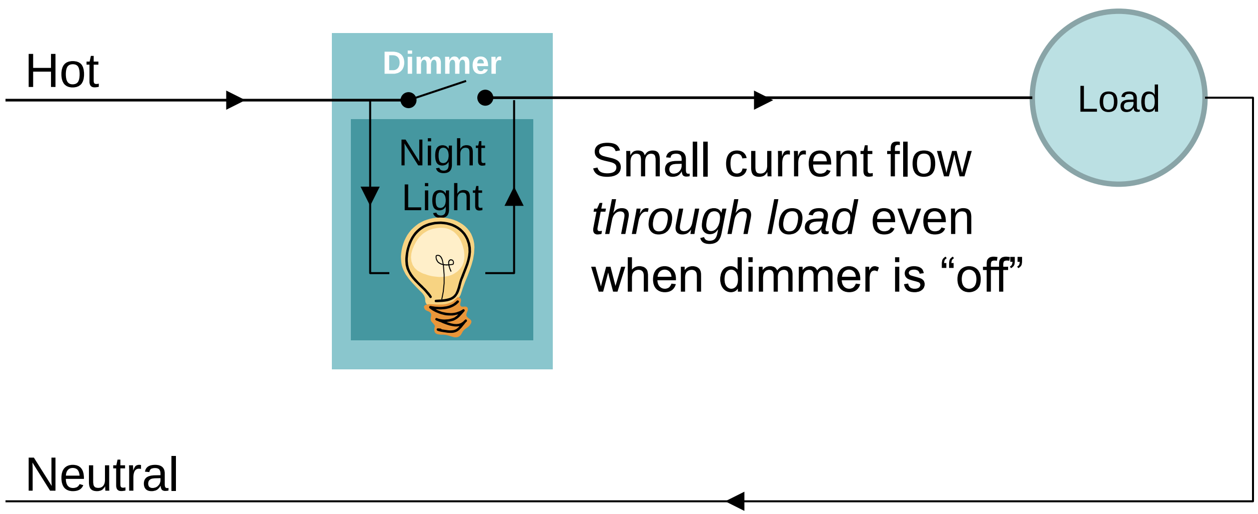
Dimmer switching element issues

- Switching element minimum holding current requirements contribute to “minimum load” requirements for dimmers
- Most existing phase-cut dimmers require a minimum load of 25-40W
- Timing circuit and “advanced features” current requirements can add to the minimum load (current) requirement

“Advanced features”

Dimmer standby current

- Dimmers without neutral need to use LED source for return path to keep “advanced features” circuitry running
- Most LED sources can not pass standby current required by dimmer



“Advanced features” 🕮

Dimmer standby current issues

- LED source flashing
  - LED source gets/accepts enough current to start, but not maintain operation
- LED source ghosting
  - LED source gets/accepts enough current to start, and maintain (low-level) operation
- Dimmer inoperable or malfunctioning
  - LED source does not accept enough current to maintain proper operation of the dimmer control
  - Most problematic for advanced dimmers

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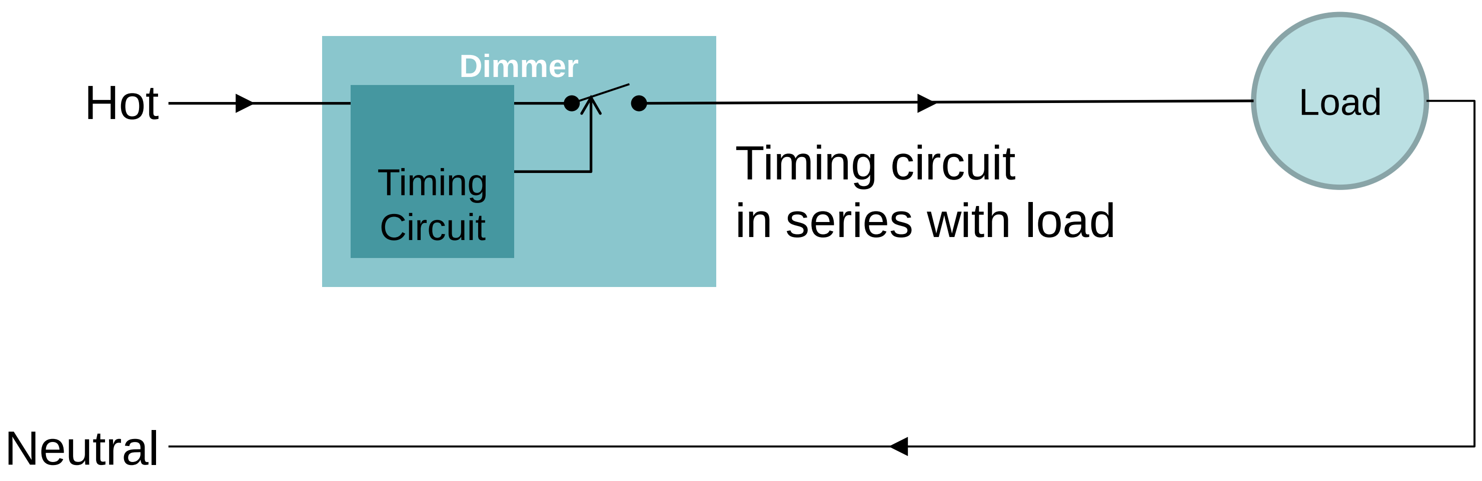
“Issue” or “feature”?

Dimmer timing element

- The timing element for phase-cut dimmers without neutral are designed to operate through the load, and expect "resistive" load characteristics
- LED load input impedance characteristics are typically not resistive, and may change as it is dimmed.



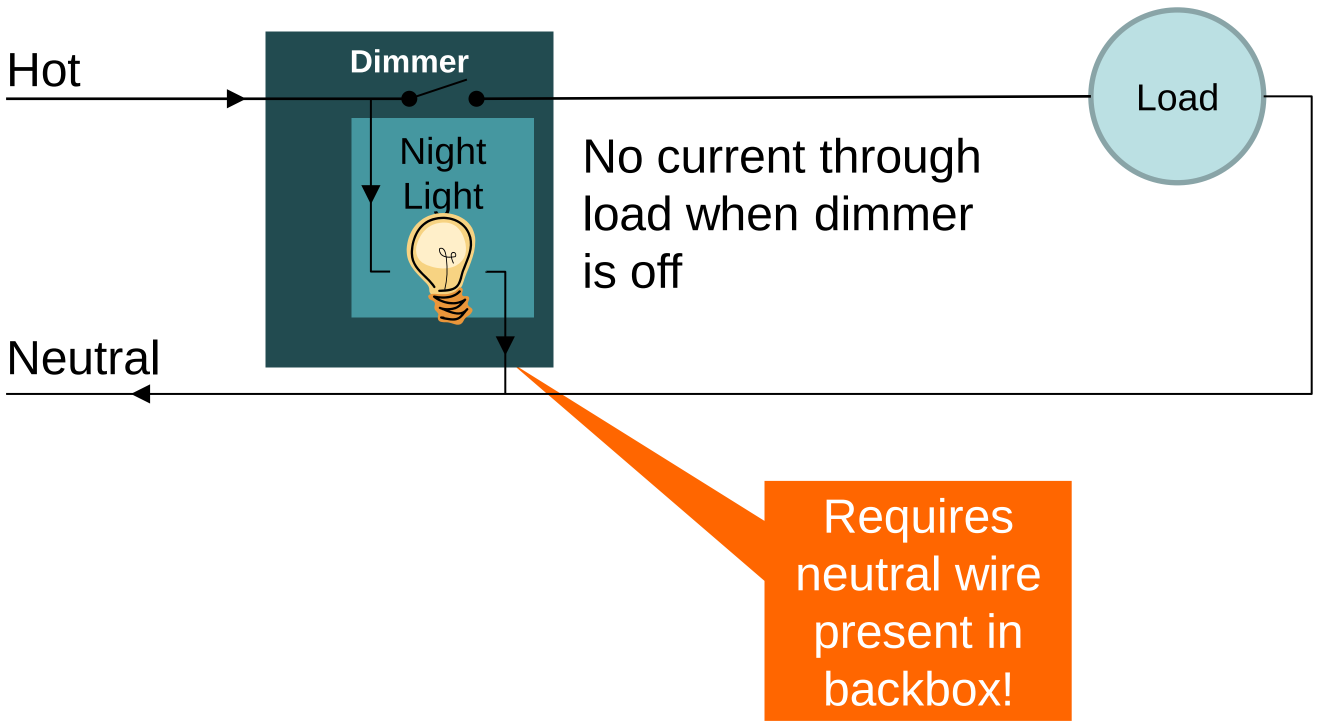
Dimmer timing element issues

- Timing element problems cause the switching element to turn on at the wrong time, aperiodically (not at consistent intervals), or both
- Any change in the switching element behavior directly affects light output
  - Turning on or off at wrong time will raise or lower light level
  - Turning on or off aperiodically causes the light level to change from cycle to cycle, likely resulting in objectionable flicker

“Advanced features”

Neutral benefits

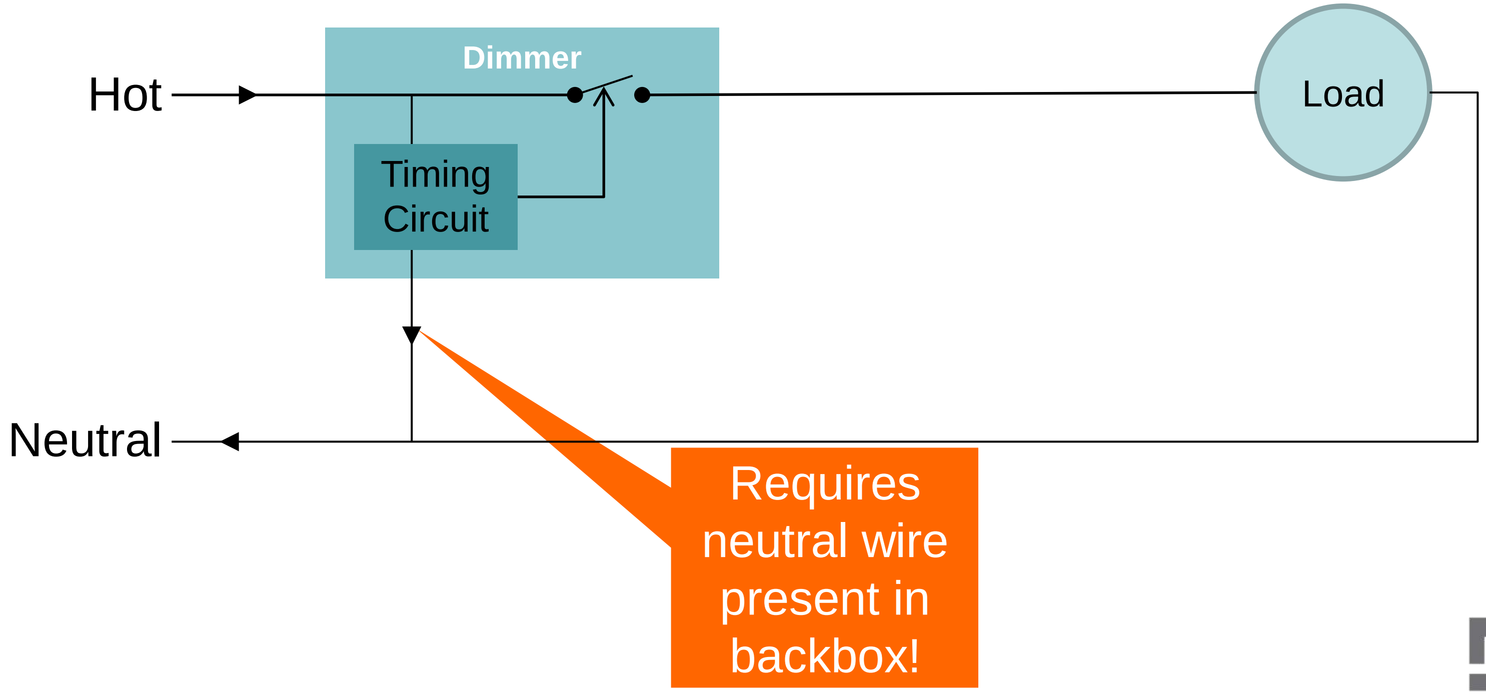
- Dimmers with neutral can direct current for “advanced features” to neutral, rather than through the LED source



Timing
Element

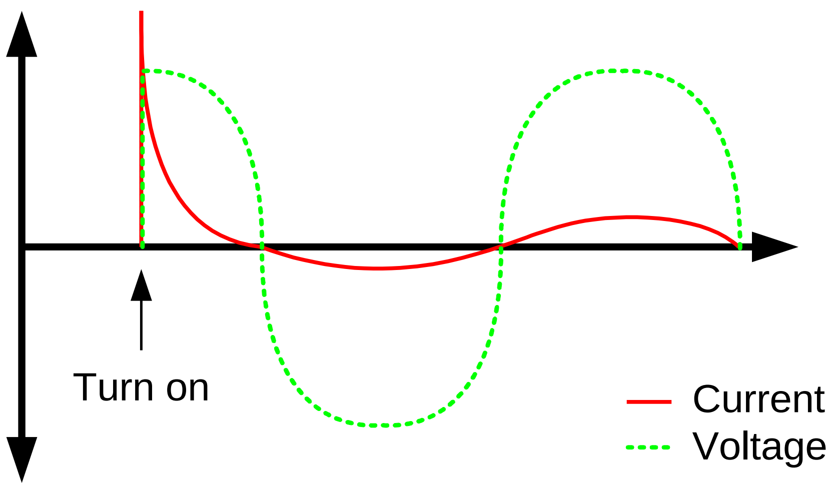
Neutral benefits

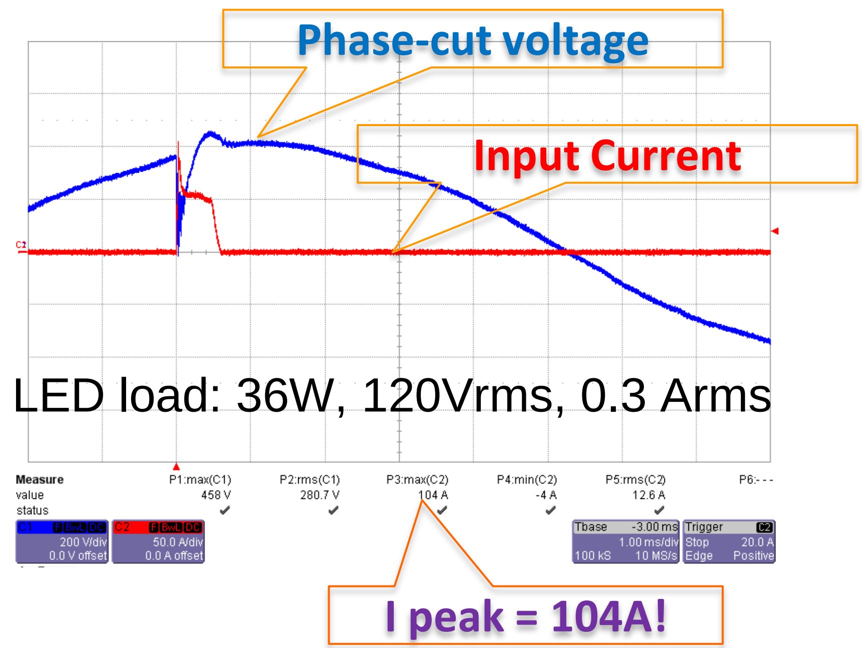
- Dimmers with neutral have a well-defined path for timing circuit current



LED source inrush current

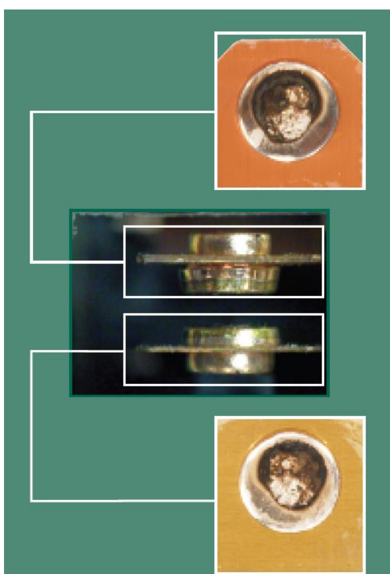
- Created by connection to power
- Occurs once per power-up
- Relevant for forward-phase and reverse-phase dimmers – and switches!





LED source inrush current issues

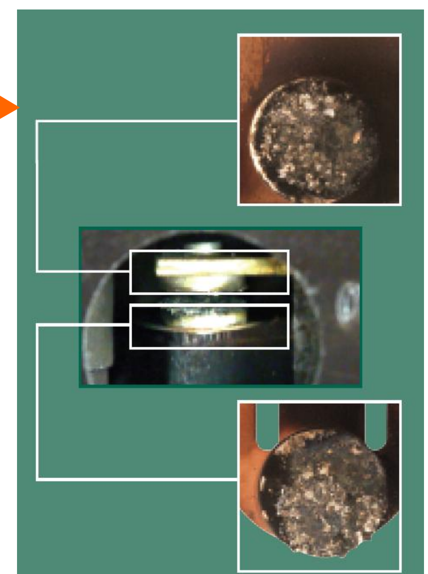
- Excessive wear on switch or relay contacts
- Premature failure (welding) of switch or relay
- Large chokes can be designed into dimmer to minimize inrush to dimmer, but may create issues of their own



Mechanical and electrical wear (high inrush)

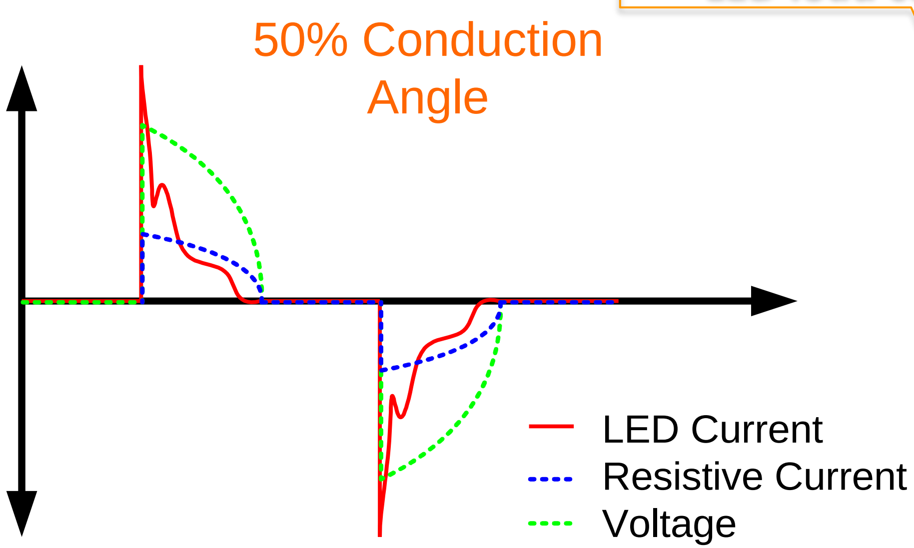
Relay contacts
120VAC, 16A
50k cycles

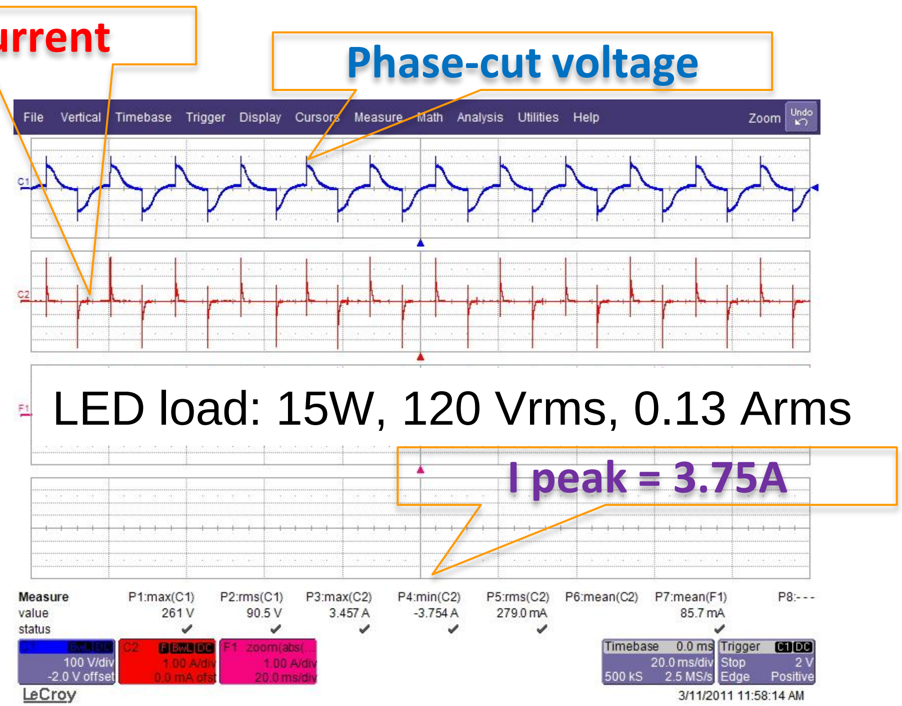
Primarily mechanical wear (no inrush)



LED source repetitive peak current

- Created by forward phase-cut, occurs every half-cycle
- Relevant for forward-phase dimmers (only)
- Commonly 5-10x Irms; can be much higher





RFI Element

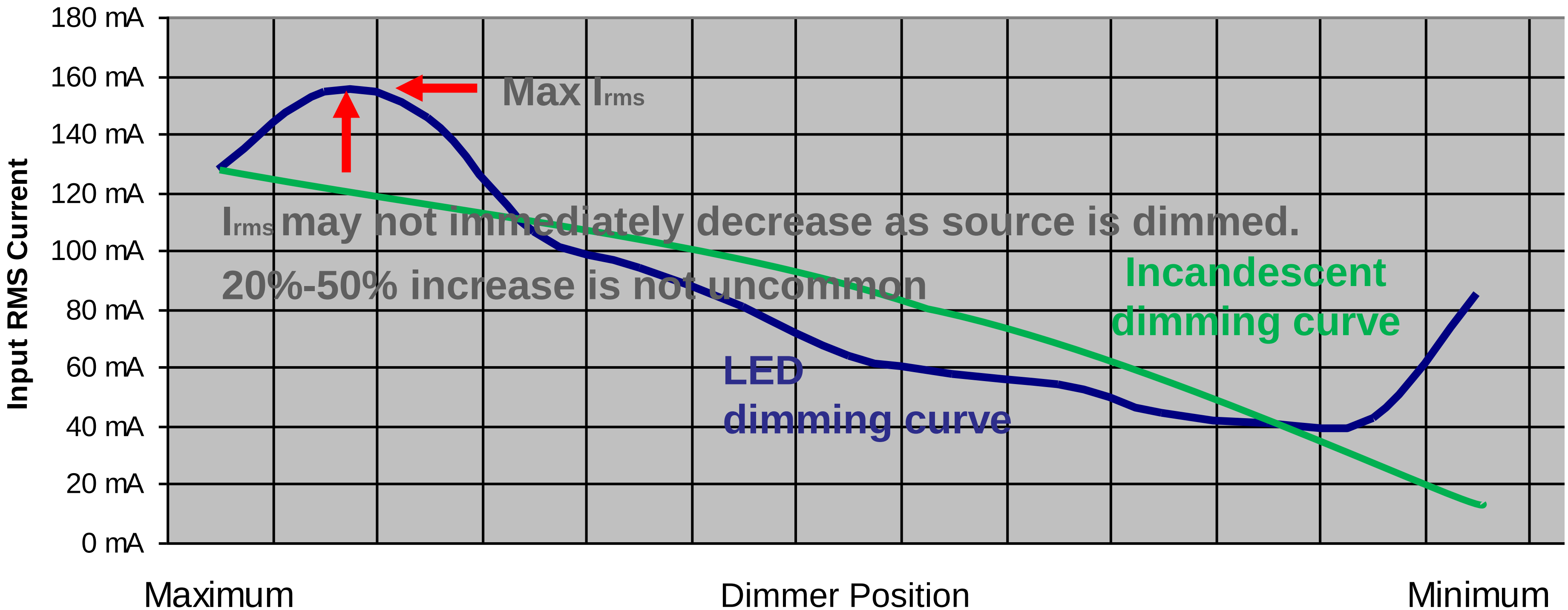
PFC

LED source repetitive peak current issues

- Varies significantly across LED products
- Often major factor determining maximum dimmer loading
- Major contributor to audible noise in light sources and controls
- Major contributor to potentially reduced control lifetime

LED source
RMS input current

Forward phase dimming curve



LED source
RMS input current issues

- Higher current in control can cause excessive (unexpected) heating of components in control or LED source
- Excessive heating can cause component stress and premature failure
- At any dimmed level
  - If Irms has gone up more than Vrms has gone down …
  - Then Pave = Irms x Vrms can go up!

Low-voltage system interfaces

- Huge issue for very popular MR16 lamps
- Two compatibility requirements
  - LED lamp/luminaire and step-down transformer
  - Step-down transformer and dimmer
- Step-down transformer characteristics are often not known (and not locatable) for retrofits
- Step-down transformer loading must sometimes be accounted for
- Both magnetic and electronic transformers designed for LV systems were designed for resistive loads
  - Pairing MLV dimmer + magnetic transformer or ELV dimmer + electronic transformer no guarantee of success with LED loads

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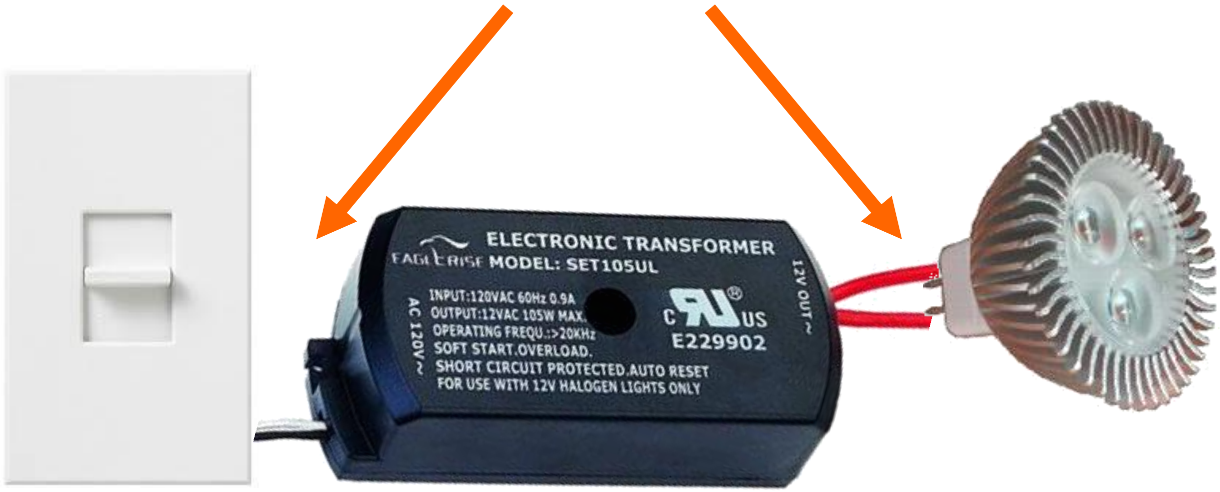
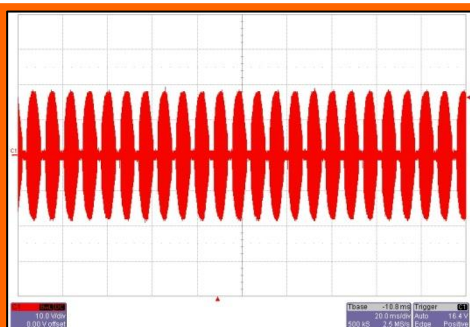
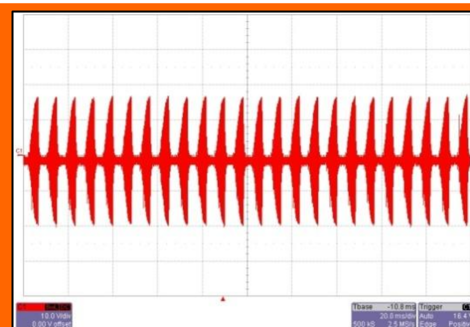
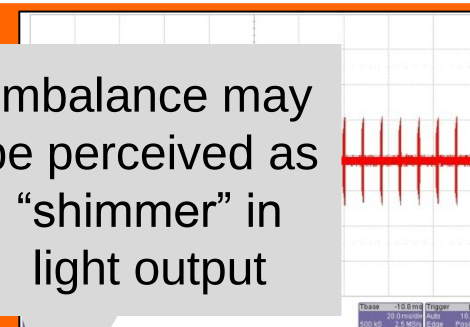
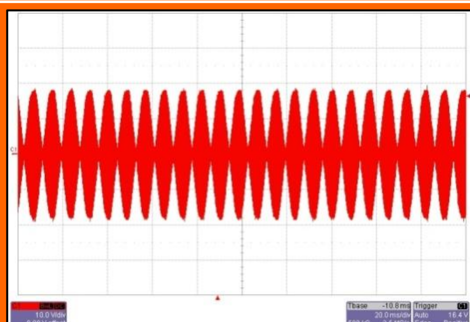
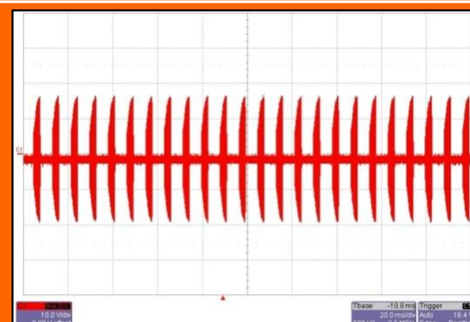
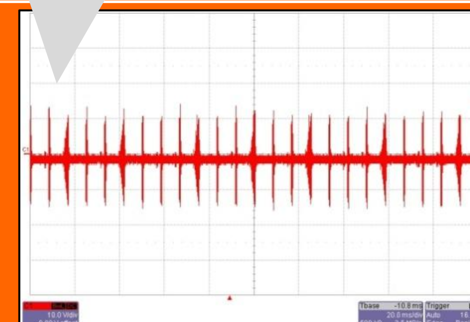
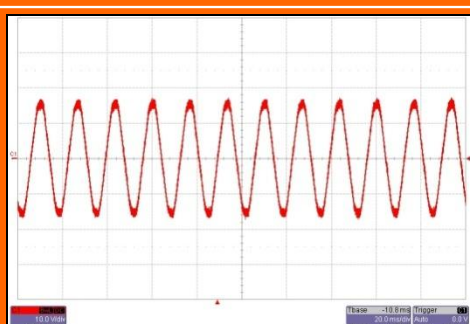
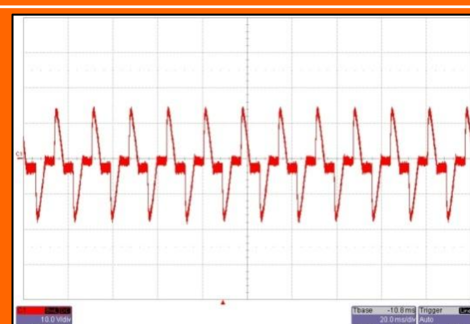
Low-voltage system interface issues

- Both dimmer and step-down transformer (ELV or MLV), may have loading requirements

Minimum load requirements both
here and here



All step-down transformers are not equal

	Switched 120V input	50% Dimmed input	10% Dimmed input
12V ELV Transformer 1			
12V ELV Transformer 2			
12V MLV Transformer			

Imbalance may be perceived as "shimmer" in light output

Nitty-Gritty summary

- The LED driver determines dimming performance
- LED driver compatibility with the dimming control determines to what degree it can deliver its designed performance
  - System variations can lead to performance variations
  - Actual dimming performance can only be determined by looking at the potential compatibility issues in the system
- Try to identify and separate issues that…
  - You have some control or influence over, and can address
  - You have little or no control over, or cannot address

Recommended practices for dimming today's LEDs

Dimming LEDs is possible, today

Learn new things

- Terminology
- Questions to ask
- Latest products
  - Power electronics IC
  - Driver
  - Dimmer
- Mock-ups

Do your homework

- LED source, by design
  - dimmability
  - control type
  - control guidance
- Control loading
- Get help making matches
- Have backup options

Selecting the right (or best) control

1. Is the LED product a lamp or luminaire?
   - Lamp
     - Typically retrofit, standard base
     - Integral, non-replaceable driver
     - Constrained to phase control
   - Luminaire
     - Often has driver options
     - Driver options yield control options: (e.g. phase control, 0-10V, DALI, proprietary)
2. What is the designed, claimed, (i.e. best-case) dimming performance of the LED product?
   - Dimming range (20%, 10%, 5% …)
   - Dimming curve (linear, logarithmic, measured, perceived …)
   - Dimming smoothness

Selecting the right (or best) control

3. Was the LED product designed for a specific type of control signal?
   - Many different dimming methods (forward, reverse phase, 0-10V, etc)
   - Very little (true) standardization
4. Does the LED product offer any control selection guidance?
   - Recommended dimmer list? If so, use it!
   - Control type? i.e. forward, reverse phase?
   - Dimmer loading? i.e. max/min number of sources per control?
   - Beware expectations of exactly the same results from any/all guidance
   - Will they ensure performance claims are met?

Dimmer loading re-cap

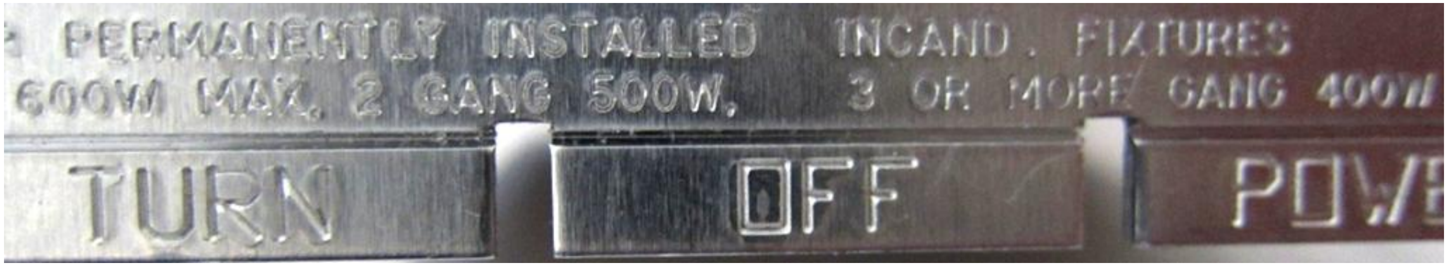
- Minimum load
  - LED loads can not draw enough current to keep dimmer switching element(s) closed, leading to erratic behavior
  - LED loads can create series impedances which disrupt dimmer timing element(s), leading to erratic behavior
  - LED loads in off state may not pass dimmer current in a manner which keeps dimmer advanced features functioning while remaining in off state
- Maximum load
  - LED loads can create stresses on dimmers above and beyond what their rated (incandescent) wattage indicates, leading to reduced dimmer lifetime

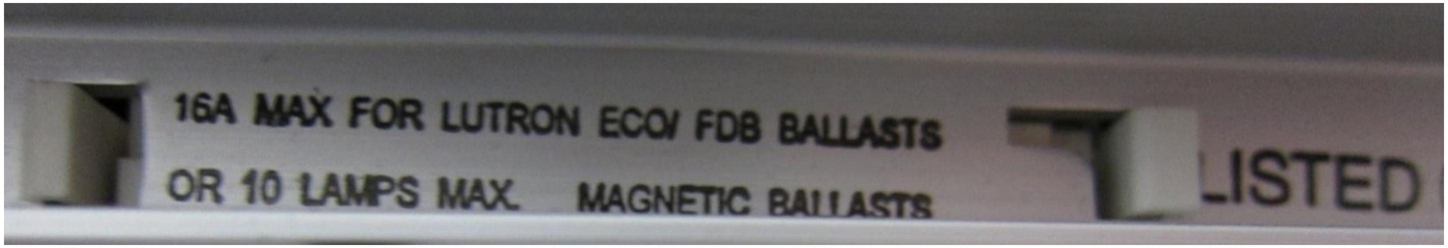
Dimmer loading rules have changed

- Minimum load varies by dimmer
- Maximum load varies by dimmer and LED source

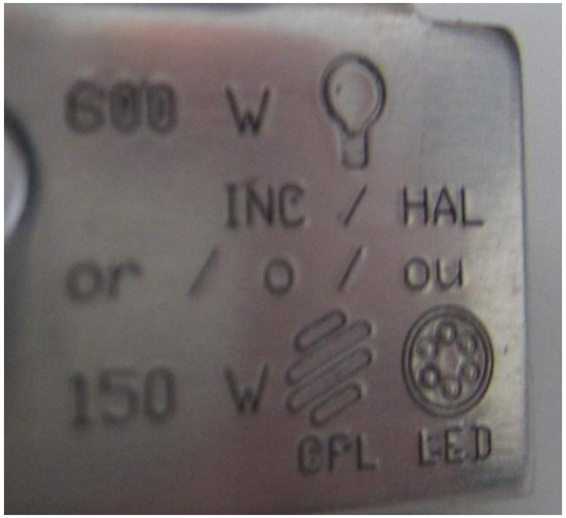
Dimmer	Source	Possible loading
600W incandescent	60W incandescent 	1-10
600W incandescent	12W LED 	~~1-50?~~ 3-10
600W ELV	50W halogen 	1-12
600W ELV	10W LED 	~~1-60?~~ 2-30

Dimmer ratings





2 load ratings!

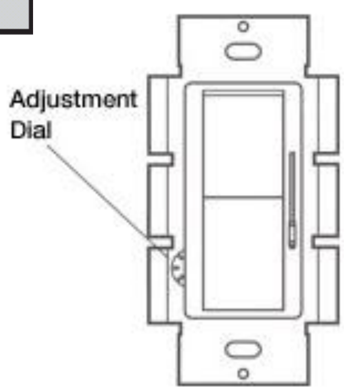


Dimmer instructions

- Mixed loads

Total CFL/LED Wattage Installed (Watts per bulb x # of bulbs)		Maximum Allowable Incandescent/Halogen Wattage*	
		No sides removed	1 side removed
0 W	+	600 W	500 W
1 W – 25 W	+	500 W	400 W
26 W – 50 W	+	400 W	300 W
51 W – 75 W	+	300 W	200 W
76 W – 100 W	+	200 W	100 W
101 W – 125 W	+	100 W	50 W
126 W – 150 W	+	0 W	0 W

- Dimming range low-end trim
  - Raises minimum dimming level
  - Reduced chance of drop-out, pop-on



GOOD dimmer manufacturer compatibility guidance

LED Product Report Card

Manufacturer: Cree
Applicable Model Numbers: LR24 – 325KA35

Manufacturer's Description
Type of Fixture: Recessed Downlight
Operating Voltage: 120 / 277 Vac
Input Power: 48W
Current: 0.4 – 1.7 A
Frequency: 50 / 60 Hz
Control Types: 0-10 VDC Control Protocol
Dimming Range: 5% - 100%
Output Power: N/A
Lumens: 3200 lumens

Lutron Test Results
Date Tested: Feb 25, 2009
Model Number Tested: LR24 – 325KA35
Smooth and Continuous: Yes
Test Notes:

Lutron Recommended Compatible Products

Product	Part Number	Fixtures per Dimmer	Measured Light Output Range (1)	Comments
Nova	NFTV	1 – 40 (4)	5% - 100%	Requires PP-120H or PP-277H
Nova T*	NTFTV	1 – 40 (4)	5% - 100%	Requires PP-120H or PP-277H
Diva	0-10V Control			Available soon
Interfaces	GRX-TVI (2)	1 – 40 (4)	5% - 100%	Range depends on dimmer selected
	GRX-TVM2 (3)	1 - 40	5% - 100%	Range depends on dimmer selected

(1) Values are based on light output using the specified dimming control, and may not be an indication of the fixture's full capability
(2) Controlled with 3-Wire Fluorescent dimmers, Homeworks, RadioRA, or Commercial Systems
(3) Controlled with Homeworks or Commercial Systems
(4) 60 fixtures for 277V applications.

Comments: The ability to set the low-end trim is available on select 3-Wire Fluorescent dimmers, Homeworks, and Commercial Systems products. Refer to product documentation or www.lutron.com for details.

Dimmer LED Bulb Compatibility

Company	Part Number	Compatible
Juno	TL201LED TRAC 12 LED Module 12W	IPI06, ATE06, 6633-P, TGI06
	120V LED Strip	None
LLF/CREE	LED LR6 2700K 12W 100mA	IPI06
Lightolier	C410LEDDL30KCCLP & C420LEDDL30KCCLP	VPE04, VPE06, IPE04, 6615, ATE06
WAC Lighting	LD-700MA-18-DIM-NIS Dimmable Constant Current LED Driver	VPE04, VPE06, VPI06, IPI06, ATE06, VRE06
	IC20LED & IC22LED	VPE04, VPE06
Cooper Lighting	LED Lamp assembly (LED 71684)	VPE04, VPE06, ATE06, IPE04
Light Emitting Designs, LLC	LED CFLA-120-10-195-SW LED PAR38-120-5-80-DL LED-PAR30-120-7-7-DL LED-A15-120-3-36DL-CL GU10 3X1W AC 85-260V Cree, LED-MR20-12-6-3-SW-60 LED-MR16-12-3-3-SW LED-MR16-12-3-48-DL	None
LEDTRONICS	PAR38-180-XPW-120AND - 120VAC	IPE04, IPI06*, 6615
	R30-123-SIW-120AMD - 120VAC	IPE04, IPI06*
	PAR20-66-XCW-120AND - 120VAC	IPE04, IPI06
	PAR30-15W-XXW-120AMD - 120VAC	6615
	PAR38-7X3W-XIW-120AMD - 120VAC	None
	LEDPAR38WW	VPE06*, VPE04*, VRE06*, ATE06*, VRM10*
Environmental Lights	12VDC LED Strip	VRM10, 6613
Philips LED driver/light engine combination	0-10V LED Driver	IP710
Lightech	LED-36-700-120-D-BF	VPE04, ATE06, VRE06

*Raise low end setting to prevent flickering or turn off at the lowest setting

GOOD lamp manufacturer compatibility guidance

MR16 LED Transformer Compatibility

Brand	Model	Input Voltage (VAC/Hz)	Power Rating (W)	Type	Number of MR16 Lamps per Transformer					
					1	2	3	4	5	6
Advance	71A9743	120 VAC, 60 Hz	75	MT	G	G	G	G	G	G
CHD	HUA1200600X2L	120 VAC, 60 Hz	60	ET	G	G	G	G	G	G
ELG	250LED100W	120 VAC, 60 Hz	100	ET	G	G	G	G	G	G
	250LED10W	120 VAC, 60 Hz	10	ET	G	N/A	N/A	N/A	N/A	N/A
	250AT075T	120 VAC, 60 Hz	75	MT	G	G	G	G	G	G
Hatch	RS12-15M-LED	120 VAC, 50-60 Hz	15	ET	G	G	N/A	N/A	N/A	N/A
	PS12-20L	120 VAC, 60 Hz	20	ET	F	F	G	N/A	N/A	N/A
	RS12-30M-LED	120 VAC, 50-60 Hz	30	ET	G	G	G	G	N/A	N/A

EnduraLED PAR38 Dimmable Indoor Flood Dimmer Compatability

Product Numbers: 40815-3, 40816-1, 40817-9, 41017-5, 41018-3, 41019-1

Brand	Series	Model	Load	Type	Dimming level Max.>Min. (flux%)) 1 lamp	Flickering 1 lamp	Flickering 3 lamp
Leviton	Decora	6161	500W	LE	99%–0	No	No
Leviton	Trimatron	6684	600W	LE	100%–0	No	No
Leviton	SureSlide	6613	600W	LE	100%–2%	No	No
Leviton	Illumatech	IP106-IL	600W	LE	100%–9%	No	at~60%
Lutron	Ariadni	AY-600P	600W	LE	100%–5%	No	No
Lutron	Diva	DV-600P	600W	LE	99%–2%	No	No

GOOD lamp manufacturer compatibility guidance

Achievable dimming, at the low end,

Best dimmers are in dark green.

Next best dimmers are in light green.

No Neutral Wire	
(Measured) (%)	(Perceived) (%)
3%	16%
bounce-back	
0%	0%
pop-on	
4%	19%
pop-on <6%	

EnvironmentalLights.com™

888-880-1880
www.EnvironmentalLights.com
11235 West Bernardo Court, Suite 102
San Diego, CA 92127

Achievable dimming, at the low end, in percent, of the high end brightness.

Best dimmers are in dark green.

Next best dimmers are in light green.

Dimmers that have a neutral wire require that the neutral wire be present in the gang box. Most newer construction has the neutral wire in the box.

Bulb Name and Part #	Part Number	Leviton Sureslide 450 Watt, 600 VA 6613-PL No Neutral Wire (Measured) (%) / (Perceived) (%)	Lutron Diva 450 Watt, 600 VA DVLV-603P No Neutral Wire (Measured) (%) / (Perceived) (%)	Lutron Skylark 450 Watt, 600 VA SLV-603P No Neutral Wire (Measured) (%) / (Perceived) (%)			Leviton Illumatech 450 Watt, 600 VA IPM06-1 No Neutral Wire We do not sell this. (Measured) (%) / (Perceived) (%)	Magnetic Low Voltage Dimmers: Lutron Maestro Wireless 450 Watt, 600 VA MRF2-6MLV No Neutral Wire (Measured) (%) / (Perceived) (%)	Lutron Maestro Wireless 450 Watt, 600 VA MRF2-6ND-120 Neutral Wire (Measured) (%) / (Perceived) (%)
PAR20 (2.5 in. dia.)									
Dimmable PAR20 (2.5 in. dia.) 7.2 Watt, E26 (Medium), 120 VAC LED Very Wide Flood 69° Warm White Halco ProLED	PAR20/7WW/VWFL/LED	3% 16% bounce-back	2% 12% bounce-back	2% poor low-end behavior			1% 11% poor low-end behavior	not compatible	not compatible
Dimmable PAR20 (2.5 in. dia.) 7.2 Watt, E26 (Medium), 120 VAC LED Flood 43° Warm White Halco ProLED	PAR20/7WW/FL/LED								
Dimmable PAR20 (2.5 in. dia.) 7.2 Watt, E26 (Medium), 120 VAC LED Narrow Flood 24° Warm White Halco ProLED	PAR20/7WW/NFL/LED								
Dimmable PAR20 (2.5 in. dia.) 7.2 Watt, E26 (Medium), 120 VAC LED Flood 46° Natural White Halco ProLED	PAR20/7NW/FL/LED								
Dimmable PAR20 (2.5 in. dia.) 7.2 Watt, E26 (Medium), 120 VAC LED Narrow Flood 26° Natural White Halco ProLED	PAR20/7NW/NFL/LED								
Dimmable PAR20 (2.5 in. dia.) 8 Watt, E26 (Medium), 120 VAC LED Narrow Flood 25° Warm White Halco ProLED	PAR20/8WW/NFL/LED2	0% 0% pop-on	0% 0% pop-on	0% 0% pop-on	0% 0% pop-on <9% meas.	not compatible	0% 0% pop-on	not compatible	not compatible
Dimmable PAR20 (2.5 in. dia.) 8 Watt, E26 (Medium), 120 VAC LED Narrow Flood 25° Natural White Halco ProLED	PAR20/8NW/NFL/LED2								
Dimmable PAR20 (2.48 in. dia.) 9 Watt, E26 (Medium), 120 VAC LED Narrow Flood 25° Warm White Toshiba	9P20/827NFL25	4% 19% pop-on <6%	4% 20%	4% 19% delay-on	3% 16% delay-on	4% 20%	4% 20%	not compatible	not compatible
Dimmable PAR20 (2.48 in. dia.) 8.6 Watt, E26 (Medium), 120 VAC LED Spot 8° Warm White Toshiba	9P20/827SP8								
Dimmable PAR20 (2.48 in. dia.) 9 Watt, E26 (Medium), 120 VAC LED Narrow Flood 25° Soft White Toshiba	9P20/830NFL25								
Dimmable PAR20 (2.48 in. dia.) 8.6 Watt, E26 (Medium), 120 VAC LED Spot 8° Soft White Toshiba	9P20/830SP8								

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LESS GOOD lamp manufacturer compatibility guidance

Dimming Specfcations:

Dimming Range	100%-10%
Type	Switch (Triac)
Available Work Mode	Trailing Edge (Recommended) Leading Edge
Compatible with Leading Dimmer Brands	

ELV: Not a TRIAC dimmer

5. Dimming – Universal voltage 120/277V with integral 0-10V dimming. For non- dimming requirements do not connect to dimming control during installation. Triac dimming available. For DALI Dimming, please consult the factory.

Compatible TRIAC Dimmers

[redacted], Aspire Series (9530XXX)
[redacted], Illumitech Series (IPI06-XXX)
[redacted] Skylark Series (S-600)
[redacted] Nova T Series (NTELV-600) ELV: Not a TRIAC dimmer
[redacted] Faedra (FAELV-500-XX) Obsolete
[redacted] Vizia (VPE06-XXX)
[redacted] Vizia (VZE04)

Show me the dimming!

<u>Mock it up</u>

- All sources
- All combinations
- Full circuits
- Especially if maintaining ANY existing equipment
- Best risk mitigation

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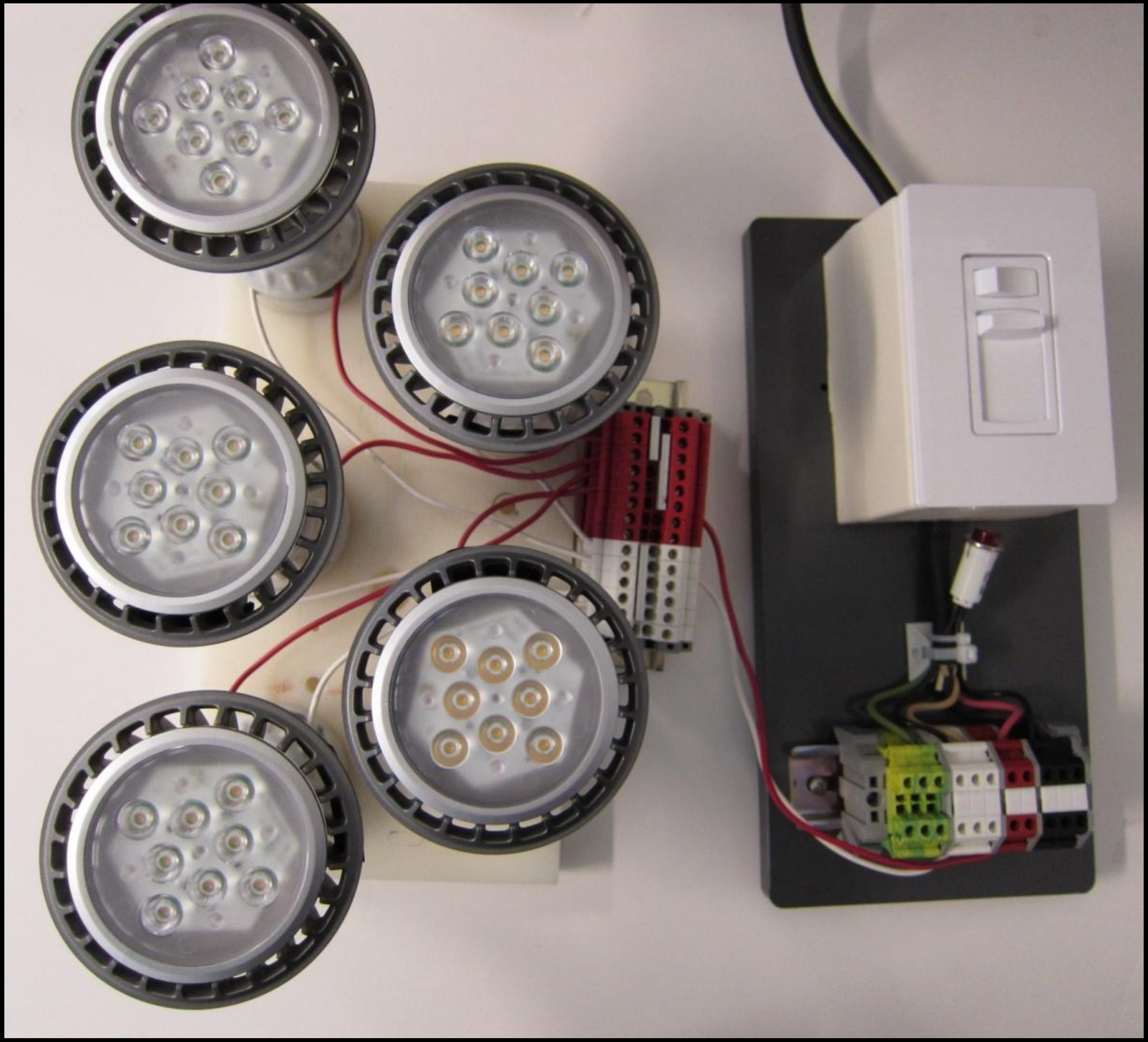
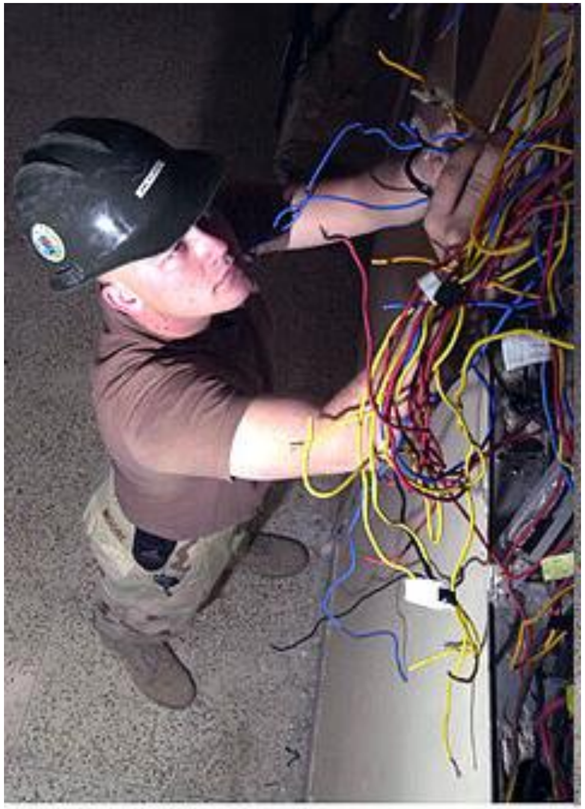
Demonstration: Mock-Up



Fixing dimming problems

- Often there are no good solutions once products are installed
- Common "fixes"
  - Change the LED source (ouch!)
  - Use a different driver (if possible?)
  - Use a different control (different performance?)
  - Add incandescent or dummy load (efficiency loss?)
  - Add additional wires and/or interface devices (costly!)
- Who is responsible? Who pays?
- Compatibility must be determined BEFORE products are ordered and installed!



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Important LED source specifications

- Designed dimming range (maximum% - minimum%)
- Dimming methodology
  - PWM (PWM frequency)
  - CCR
- Designed dimming curve (linear, square-law, s-curve)
- Flicker
- Low-voltage?
  - Step-down transformer requirements, selection guidance
- Control selection guidance
- Beware substitutions, model updates (all bets are off)

Important dimmer specifications

- Loading limits (maximum, minimum)
- Advanced features
- Trim requirements
- Availability of neutral
- Compatible LED source guidance
- Beware substitutions, model updates (all bets are off)

Standards & Specifications

Standards & Specifications

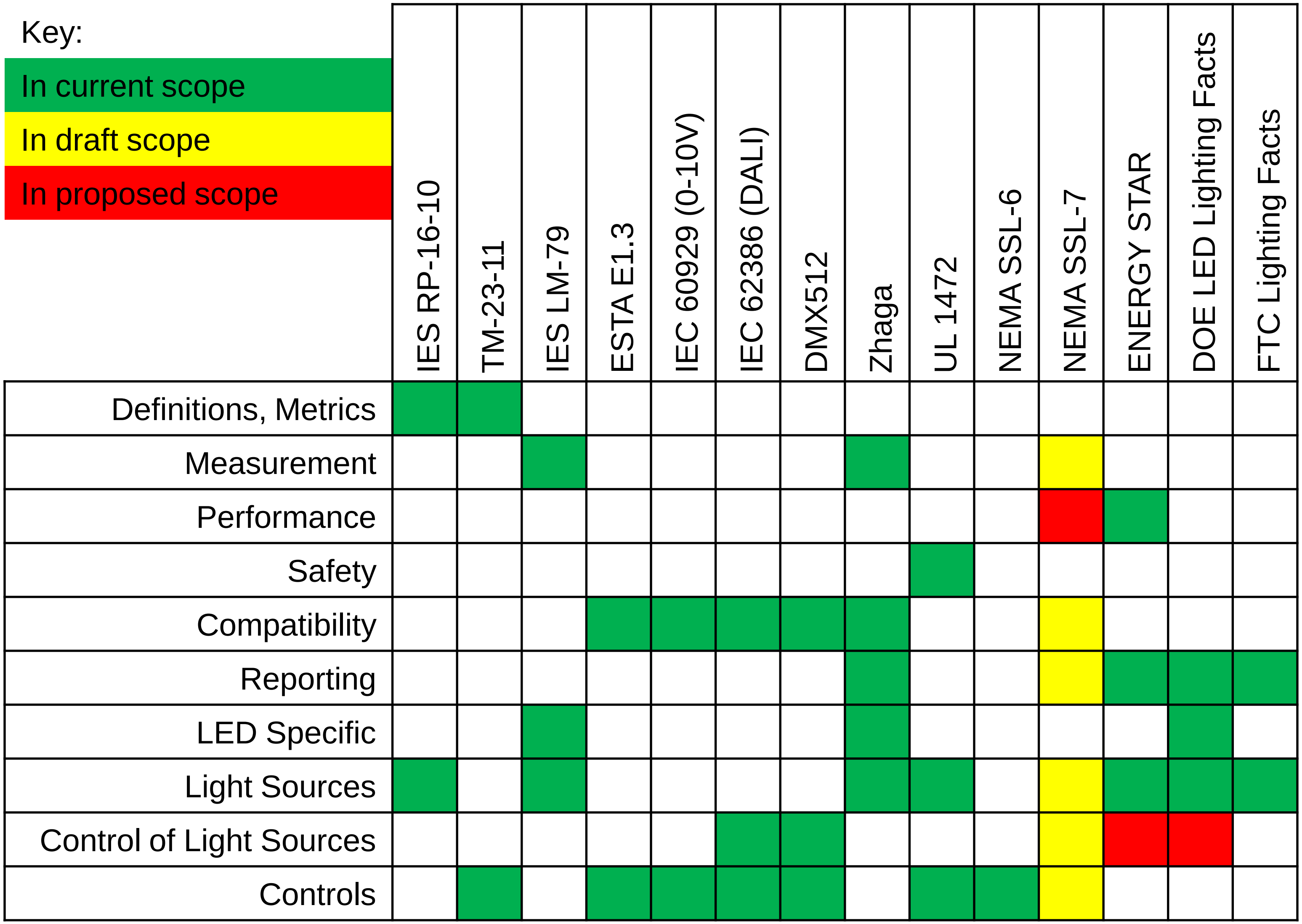
- Definitions, metrics
- Measurement procedures
- Performance requirements
- Safe operation
- Compatibility
- Reporting requirements and formats

- Updates
  - UL
  - DOE LED Lighting Facts
  - ENERGY STAR
  - Zhaga
  - Zigbee Light Link
- In development
  - NEMA SSL-7
  - Insta DLT / IEC 62756-1
- New approaches

Standards & Specifications Landscape

Government	Industry	Not-for-profit	For-profit
U.S. DEPARTMENT OF ENERGY	NEMA	ANSI	UL
energy	Zhaga	IEC	SA
energy saving trust	EMerge ALLIANCE	IES Illuminating ENGINEERING SOCIETY	DVE
	ZigBee Alliance	IEEE	Intertek
			DEKRA
			LIGHTFAIR INTERNATIONAL The future. Illuminated. 2012

Standards & Specifications Review



Underwriters Laboratories

- UL 1472 “Solid-State Dimming Controls”
  - Applies only to stand-alone wall-box controls
  - Covers “lighting loads of the ballast [ELV], transformer [MLV], or tungsten-filament [incandescent] type”
  - LED loads must be individually tested and listed in dimmer’s UL file as a “matched pair”
  - Electrical characteristics of lamp must fall within design limits of dimmer
- Other UL standards address other controls
  - Treat LED loads differently
  - Do not require matched-pair listings
  - Examples
    - UL 508 “Industrial Control Equipment”
    - UL 244A “Solid-State Controls for Appliances”

PWM, CCR implications with UL & CSA

- UL and CSA have different Class 2 voltage limits for PWM and CCR LED driver outputs
- Class 2 LED drivers operating between 42.4V and 60V can use CCR where UL is accepted, but not in Canada

	PWM Class 2 Limits	CCR Class 2 Limits
UL	42.4V maximum (for frequency > 200Hz)	60 V maximum
CSA	42.4V maximum	42.4V maximum

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Safety Certification Challenges

- UL does not accept other data (e.g. ETL)
  - UL1472 requires matched pair test and listing for LED sources
  - UL will not accept matched pair data for LED sources which are not UL listed
- CE mark not available for LED-specific controls
  - CE mark requires compliance with IEC standards
  - IEC 61000-3-2 sets harmonic current limits for phase-cut controls
    - Exceptions (higher limits) are available for controls used with incandescent sources (ONLY)
    - Impossible for controls to meet IEC limits with LED sources due to high harmonic currents

Zhaga overview

- Industry consortium developing specifications which allow for the interchangeability of LED light engines (LED module + Electronic Control Gear) for all applications in general lighting
- Multiple application-specific specifications
- Covers both integrated and separate electronic control gear (LED drivers)
- Tested and certified by independent labs (e.g. UL, DEKRA)
- In-scope: Standardized mechanical, photometric, thermal, and electrical interfaces
  - Standardized control interface(s) addressed by reference to outside specifications (e.g. IEC 60929, IEC 62386)
  - Forward phase-cut control will be addressed by NEMA SSL-7
- Out-of-scope: Performance, Quality, Safety, Interface between LED Module and Electronic Control Gear

Existing Zhaga Specifications

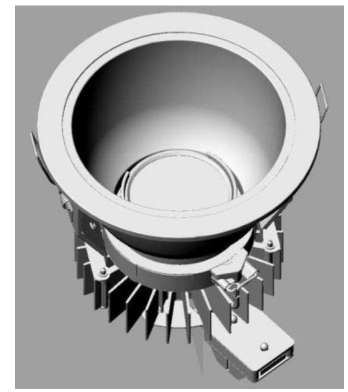
In February 2011, Zhaga approved the specification for a downlight engine with integrated control gear.

Light Engine

+

Interface

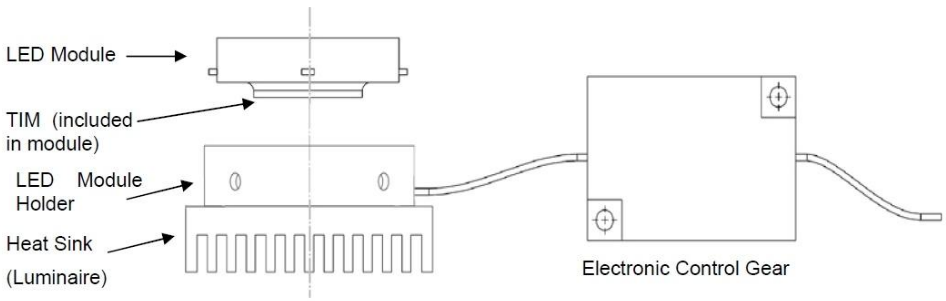
=



Downlight

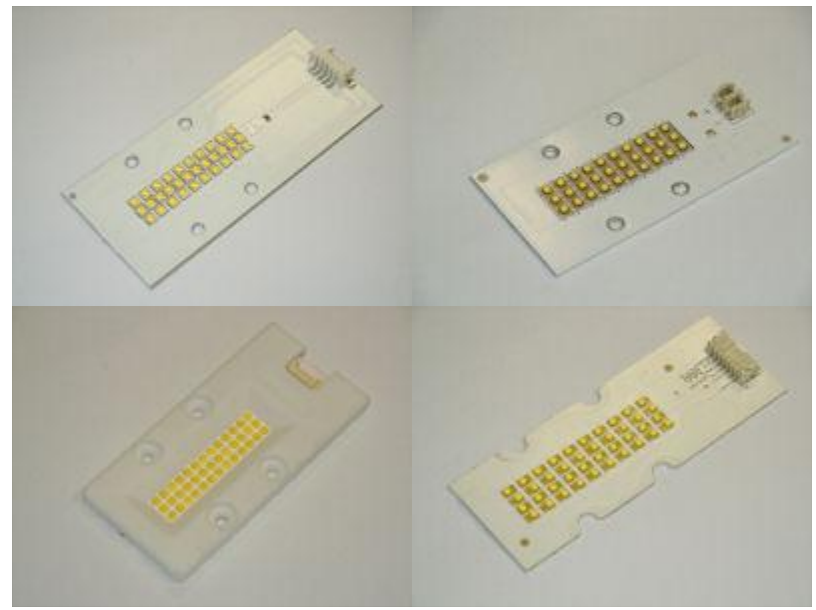
In June 2011, Zhaga approved the specification for a spotlight engine with separate control gear.

Existing Zhaga Specifications



In September 2011, Zhaga approved the specification for a socketable light engine with separate control gear.

In December 2011, Zhaga approved the specification for a socketable light engine with integrated control gear.



In March 2012, Zhaga approved the specification for a flat emitter streetlight engine with separate control gear.

Zhaga status

- Initial round of 30 products approved for showing Zhaga logo were on display at Light+Building in April 2012

light+building

Hall 2.0
OSRAM AG, B10+B50
Zumtobel AG, B29+B30

Hall 3.0
TRILUX GmbH & Co. KG, D11+E11
AB Fagerhult, D91

Hall 3.1
iGuzzini illuminazione Spa, E31

Hall 4.0
TRILUX GmbH & Co. KG, B11
BJB GmbH & Co. KG, B12
Panasonic Corporation, B50
Alux-Luxar GmbH & Co. KG, C51
A.A.G. STUCCHI s.r.l. u.s., D11
Tridonic GmbH & Co. KG, D15
Molex Incorporated, F41
Arditi S.p.A., F81

Hall 4.1
General Electric Company, D10
DEKRA Certification B.V., G06
Neonlite International Limited, H70
Everlight Electronics Co., Ltd., K10

Hall 4.2
Toshiba Corporation, G10+G20
LG Innotek, G25
Samsung Electronics Co. Ltd., G41
Citizen Electronics Co., Ltd., H41
Bridgelux, Inc., J31
Nuventix, K87

Hall 5.0
NERI spa, C20

Hall 8.0
Ideal Industries, Inc., G09

Hall 10.1
Shanghai Yaming Lighting Co., Ltd., A47
Zhejiang Shenghui Lighting Co., Ltd., B51
Lustrous Technology Ltd., C10
Epistar Corporation, D60

Forum
Philips Lighting B.V.

- Other product releases, Zhaga specifications in progress
- Market adoption TBD

NEMA SSL-7 Overview

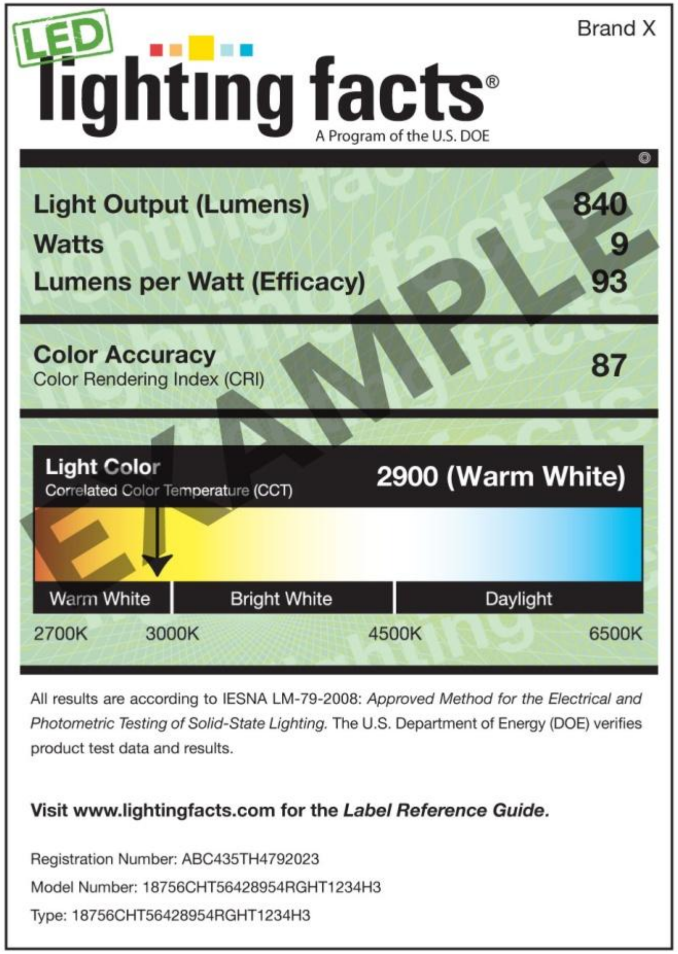
- Part 1 (interoperability): in development; ETA 2H 2012
- Part 2 (performance): initiated upon completion of Part 1
- Defined compatibility and performance for SSL-7 compliant phase-cut controls and lamps/luminaires
  - Current scope covers forward phase-cut controls only
  - Current scope covers light sources which connect to electrical branch circuit, and have electronic power supply
- Defines design specifications for lamps/luminaires and controls
- Defines compliance test procedures for lamps/luminaires and controls

SSL-7 Features

- Predicable, specified performance
  - Minimum definition for dimmable
  - Room for product differentiation
- Compliant lamps/luminaires will have performance ratings that will be valid with all compliant dimmers
  - Dimming range (relative maximum output, minimum output)
  - Dimmer loading characteristics
- Compliant dimmers will have performance ratings that will be valid with all compliant lamps/luminaires
  - Reliable operation
  - Load ratings (maximum and minimum, if necessary)

DOE LED Lighting Facts

- Reports selected IES LM-79 data
  - Luminous flux
  - Power
  - Efficacy
  - CRI
  - CCT
- Not a performance criteria (NO PASS/FAIL)
- Proper use monitored by DOE
- Coming soon
  - Lumen maintenance (label option)
  - Warranty (label option)
  - Dimming information (online database option)



http://www.lightingfacts.com/

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Dimming to comply w/ENERGY STAR

EPA Luminaires v1.1

- Dimming requirements, all luminaires marketed as dimmable, solid state:
  - The luminaire and its components shall provide continuous dimming from 100% to 35% of total light output.
  - Step dimming, if employed, shall provide at least two discrete light output levels ≥ 35% of total light output and not including 100% output.
- Operating frequency requirements, directional and non-directional luminaires, solid-state:
  - Dimming operation shall meet the requirement at all light output levels.

http://www.energystar.gov/ia/partners/product_specs/program_reqs/Final_Luminaires_Program_Requirements.pdf?c076-f95c

Dimming to comply w/ENERGY STAR

EPA Lamps v1.0, Draft 1

- Comment period ended December 9, 2011
- Dimming requirements: all lamps marketed as dimmable:
  - TBD
  - Note: EPA is working with industry stakeholders and the Lighting Research Center (LRC) to develop a definition, method of measurement, and compatibility metric for dimmable lamps.
  - The Agency seeks to establish a definition of dimming which emphasizes quality, ensuring that qualified dimmable lamps dim down to levels meeting consumer expectations, are compatible with the majority of the installed base of dimmers, and are free from noise and flicker, among other criteria.
  - Important ongoing and completed work by ANSI, ASSIST, LRC, NEMA, Pacific Northwest National Laboratory, and others will be included in this effort, the results of which will be entered into a subsequent draft for partner and stakeholder comment.

http://www.energystar.gov/ia/partners/prod_development/new_specs/downloads/luminaires/ENERGY_STAR_Lamps_V1_0_Draft_1.pdf?8c53-08ca

Dimming to comply w/ENERGY STAR

DOE Integral LED Lamps v1.4

- In place until EPA Lamps v1.0 applies
- Dimming requirements
  - Lamps may be dimmable or non-dimmable.
  - Minimum efficacy, light output, CCT, CRI, and power factor of dimmable lamps will be confirmed with the lamp operated at full power.
- LED operating frequency requirements
  - Dimming operation shall meet the requirement at all light output levels.

http://www.energystar.gov/ia/partners/product_specs/program_reqs/Integral_LED_Lamps_Program_Requirements.pdf?17cf-f07d

New approaches to control

New control protocols	New system architectures
• Powerline carrier – Digital modulation of AC power – Coincident AC power and control signal • Wireless – Digital open spectrum communication – Separate AC power and control signal	• Centralized power supply – Low-voltage (CV) wiring between power supply and lamp/luminaire – Coincident or separate AC power and control signal • Centralized LED driver – Low-voltage (CC) wiring between driver and lamp/luminaire – Coincident or separate AC power and control signal

Insta DLT / IEC 62756-1 Overview

- Digital Load Line Transmission
  - Coincident AC power and control signal
  - Powerline carrier, NOT phase-cut
- Digital, one-way communication
- Developed by INSTA and OSRAM to overcome challenges with dimming CFLs in Europe
- Using existing wiring
- Easy to assign single/individual control devices to one or many light sources without added wiring

Insta DLT / IEC 62756-1 Features

- 2 bi-phase bits per AC half-cycle modulation
- Control of light level, chromaticity or CCT, and manufacturer specific messages
- Supports four lighting zones
- Open standard, freely licensed
- Status
  - Available through Insta (http://www.insta.de) now
  - IEC 62756-1 in development; ETA 2013

ZigBee Alliance Light Link

- Separate AC power and control signal
  - Requires new control and LED driver
- Digital, two-way communication
- Developed by ZigBee Alliance
- Wireless mesh communication built on IEEE 802.15.4 PHY and MAC
- Easy to assign single/individual control devices to one or many light sources (without added wiring)

Overview:
http://www.zigbee.org/Standards/ZigBeeLightLink/Overview.aspx

Light

Smart, easy-to-use lighting control designed for consumers.

ZigBee Alliance Light Link Features

- Low-cost (leverages other Zigbee applications)
- Wire-free installation, retrofit
- Device authentication, AES 128 encryption
- ZigBee Certified compliance testing
  - Lighting control market interoperability?
- Device assignment and commissioning?
- Status
  - Recently released (April 17, 2012) standard now available to ZigBee Alliance members
- Market adoption TBD
- More info on May 16, 2012
  - "Exploring New Lighting Opportunities with ZigBee Light Link"
  - http://www.zigbee.org/Events/Webinars.aspx

Light

Smart, easy-to-use lighting control designed for consumers.

Standards & Specifications Summary

- Current standards help alleviate but don't eliminate issues
- Zhaga standards released, products on the market
  - No impact on dimming
  - Market adoption TBD
- NEMA SSL-7 promises to improve phase-cut dimming performance for compliant products
  - Final scope TBD
  - Market adoption TBD
- New technologies and approaches may or may not have major impact…

Closing Comments

The importance LED dimming continues to grow

- Manufacturers realize problems are not going to go away, or solve themselves
- Customers are demanding solutions
- Greater collaboration, innovation resulting in slow but steady progress
  - New generations of lamps and controls are now being built with LED dimming performance specifically in mind
  - Standards can/should reduce dimmer uncertainties for LED sources, and LED source uncertainties for dimmers

LED dimming is possible today

- High performance LED dimming, while not easy, is possible …today
- What to expect in the near future
  - Dimming LEDs will continue to get easier
  - Fewer dimmer loading problems
  - Your success will continue to correlate to your willingness and ability to learn new things
- What not to expect in the near future
  - Broad compatibility with most installed dimmers
  - Broad availability of LED sources that can dim to 1% on many dimmers
  - Elimination of compatibility testing as the best predictor of performance … but stay tuned?

Change continues to challenge existing assumptions

- LEDs are eminently dimmable
- Dimming LED products in the real world is still currently challenging
  - Particularly with phase-cut dimmers
  - Wide variation in compatibility and performance
  - Little can be assumed
  - Not all claims are equal
  - Difficult to predict without full mock-up testing
- Past performance is no guarantee of future results
- New standards, approaches could be game-changing
- New approaches hold promise of overcoming many of today's major challenges

Q & A

Dimming LED sources: what's working and what still needs fixing

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