LEDucation
Trade Show and Conference

Designers Lighting Forum

21st Century Lighting Technology & Historic Artifacts, Fine Art, Ancient Infrastructure.

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Questions related to specific materials, methods, and services will be addressed at the conclusion of this presentation.

Abstract

The Museum application is the framework for this conversation.

Intersections: Technology’s Impact and opportunity illuminating ancient art & objects in old infrastructure and new construction; converting from incandescent to LEDs in a world class cultural institution.

Learning Objectives

Compatibility Attendees will learn the discerning criteria required to vet and qualify various manufacturers sources and components to ensure compatibility for flicker free dimming. – Color, dimming characteristics – flexibility importance, screw base/ plug-and-play/ adjustable optics, resource waste concern/ land fill, retrofit capabilities, relationship with manufacturers, universality (track fittings, standard lens sizes, base types), sustainability.

Coexist Attendees will gain a deeper understanding of the exacting considerations required to specify a multitude of types across applications with competing hierarchy (i.e., daylight, conservation, ambient, budgetary, display, safety, wayfinding) in the same space.

Capital Expense Learn why slow is best to test, to research. To educate stakeholders to identify and focus on opportunities to positively impact the P&L statement. Funding sources – LED 2.0 upgrade (components rather than source itself – control systems, drivers, dimmers). Proprietary dimming systems – compatibility over various updates/ versions, locked out of systems, staff training/ talent retention/ response time.

Color Conundrum We don't see color; understand how the perfect source was flawed; how 21st century technology reveals rivals and confuses.

The Museum Environment

The Metropolitan Art Museum, 5th Avenue

The Great Hall

The Met’s lighting through the years

1890

1910

1920

1930

1950

2000

Special Exhibitions

Inspiring Walt Disney, 2021

Charles Ray, 2021

Tree and Serpent, 2023

The Tudors, 2022

Gallery Reinstallation Projects

Afro Futurist Period Room, 2021

Northern Renaissance, 2023

Belfer, 2023

Wang, 2024

Gallery Reinstallation – Northern Renaissance

Before

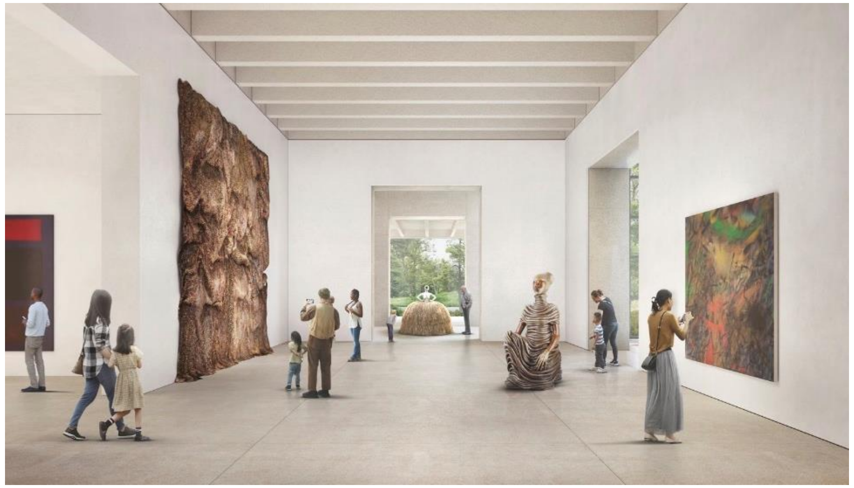
After

Capital Projects

British Galleries, 2020

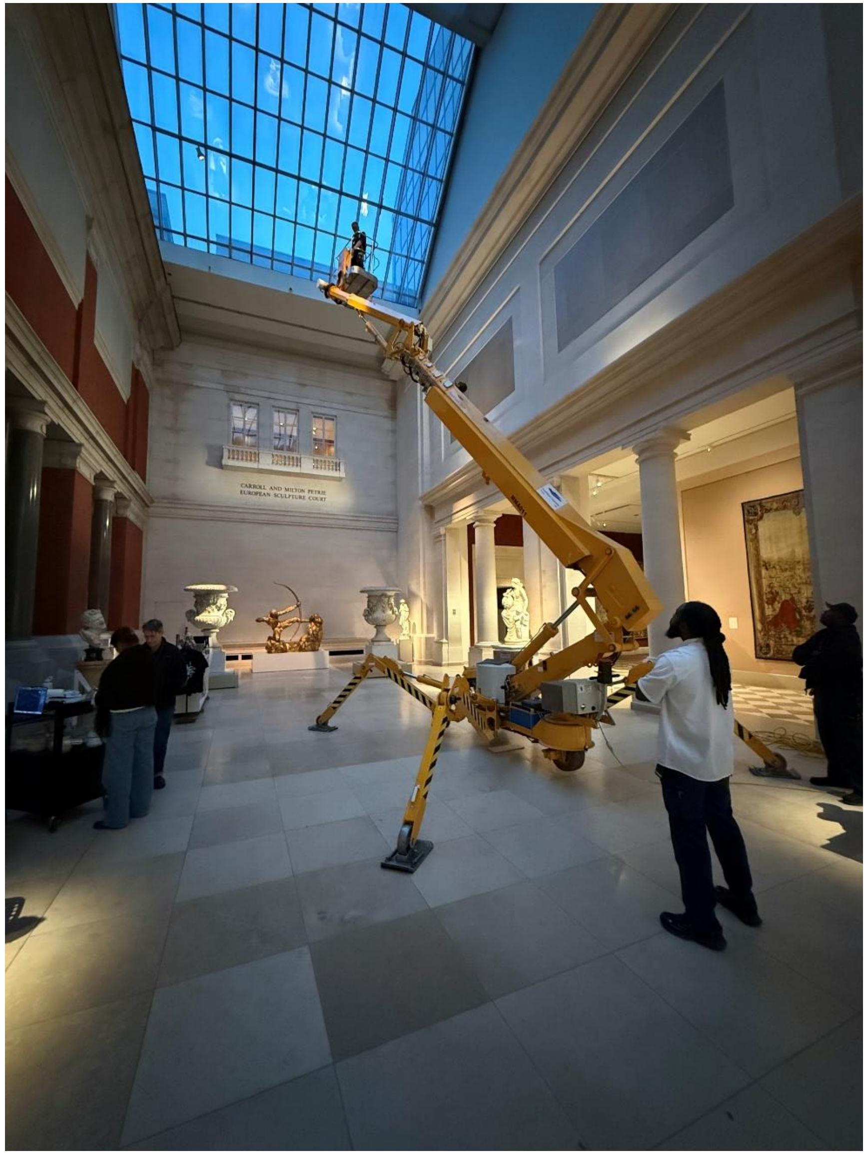
Michael C. Rockefeller, 2024

Great Hall Gallery, 2026

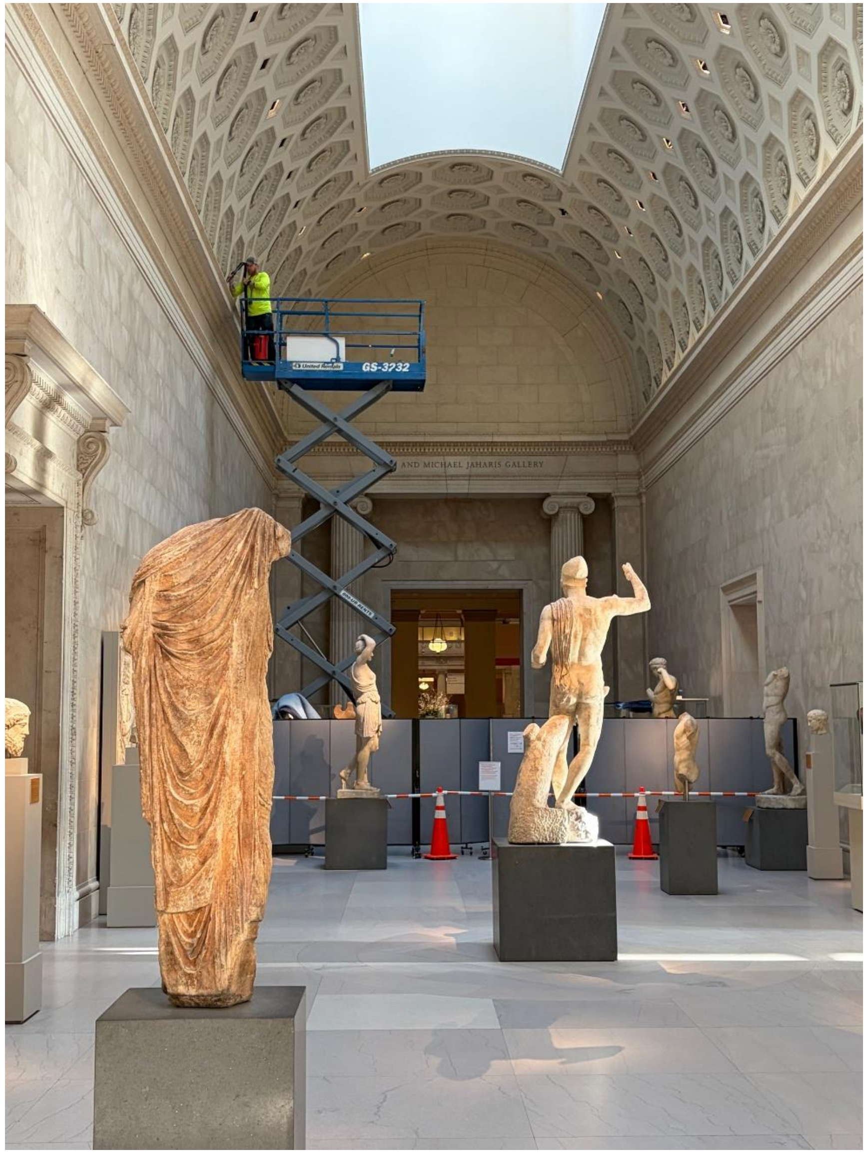


Tang Wing, 2030

Museum Wide LED Upgrade



Petrie Court, 2026



Jaharis Corridor, 2026

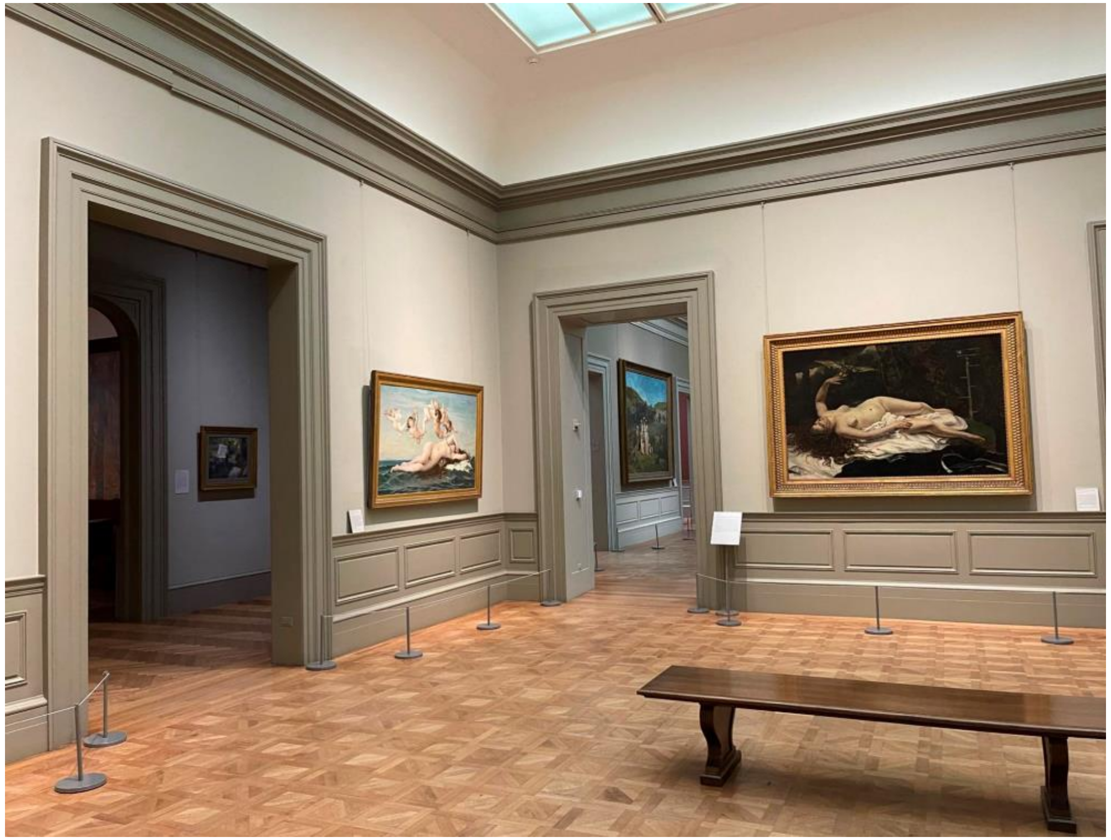
Mock-up Phase / Egypt

Legacy

LED

Mock-up Phase / 19th Century Paintings

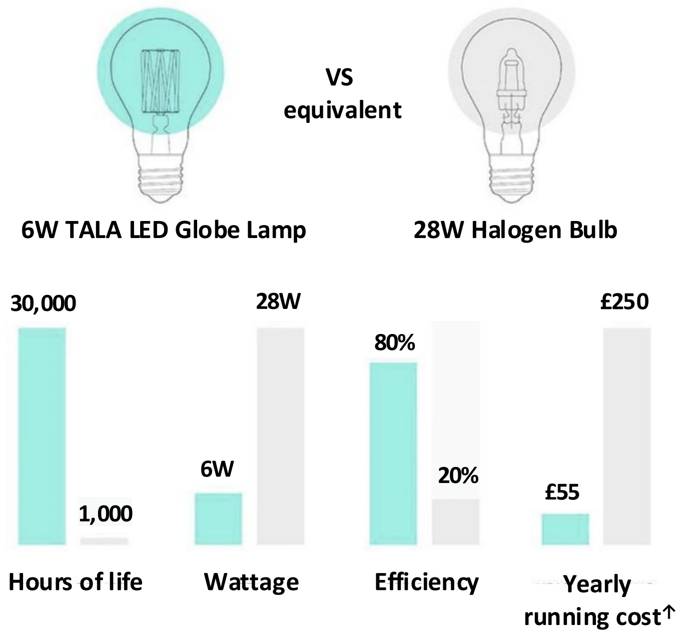
Legacy



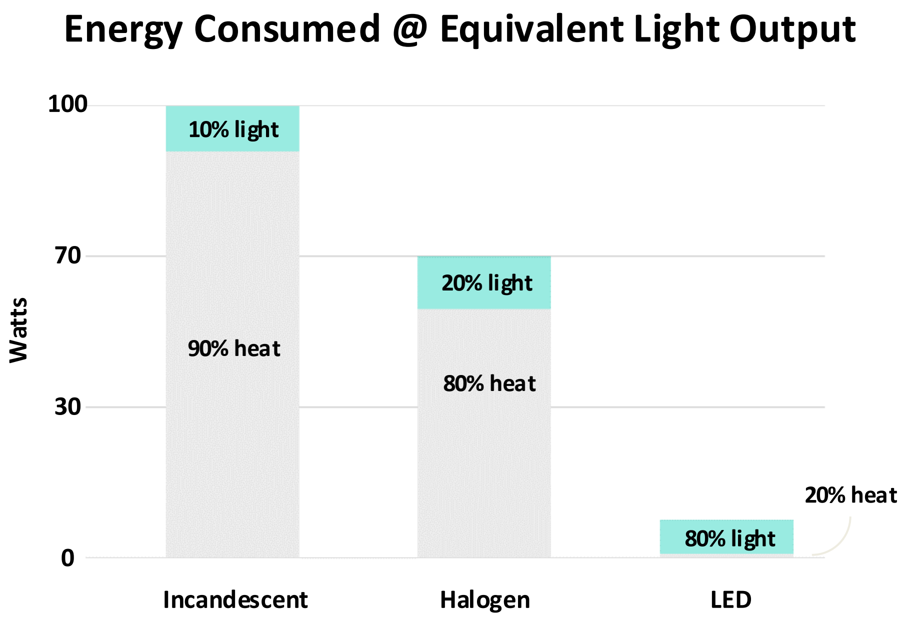
LED

Reduce our Carbon Footprint

Embrace a useful and usable source



↑25 Bulbs, 6 hours a day for one year



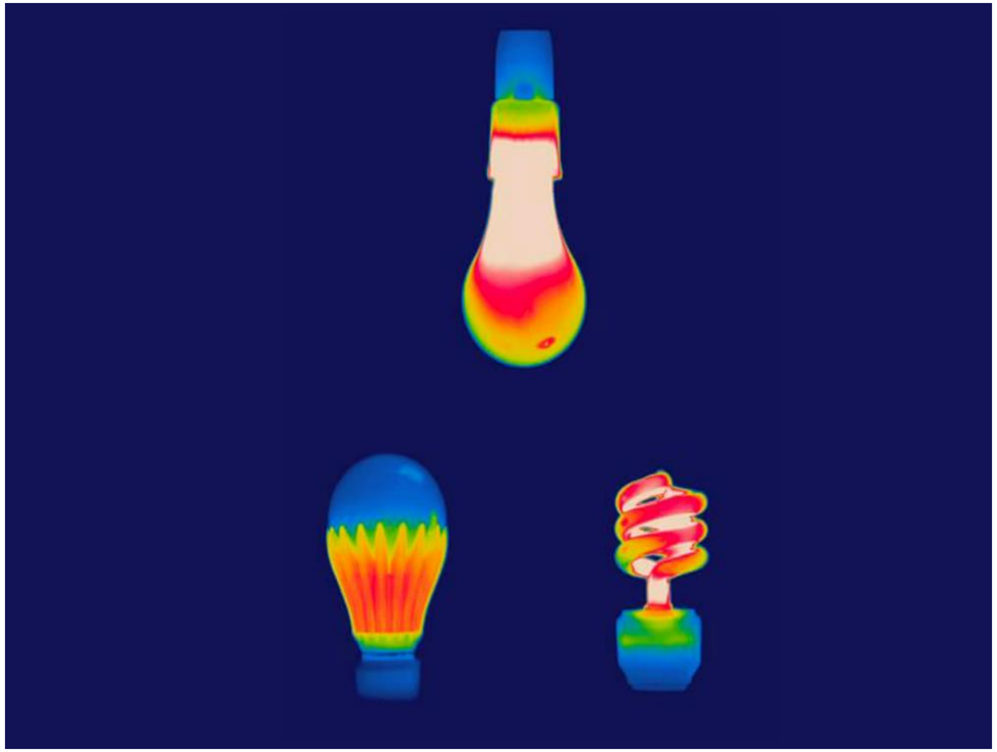
Become Sustainably Responsible

Higher upfront cost but much longer life span, with less maintenance and less physical waste

Product	12W LED	15W CFL	Energy Saving 43W Halogen	Traditional 60W Halogen	Trad. 60W Incandescent
Lifetime Hrs.	25,000	10,000	2,000	1,000	1,000

Reduce Radiant Heat

LEDs burn cooler and vent out the back, which will result in a cool and improved environment for the art

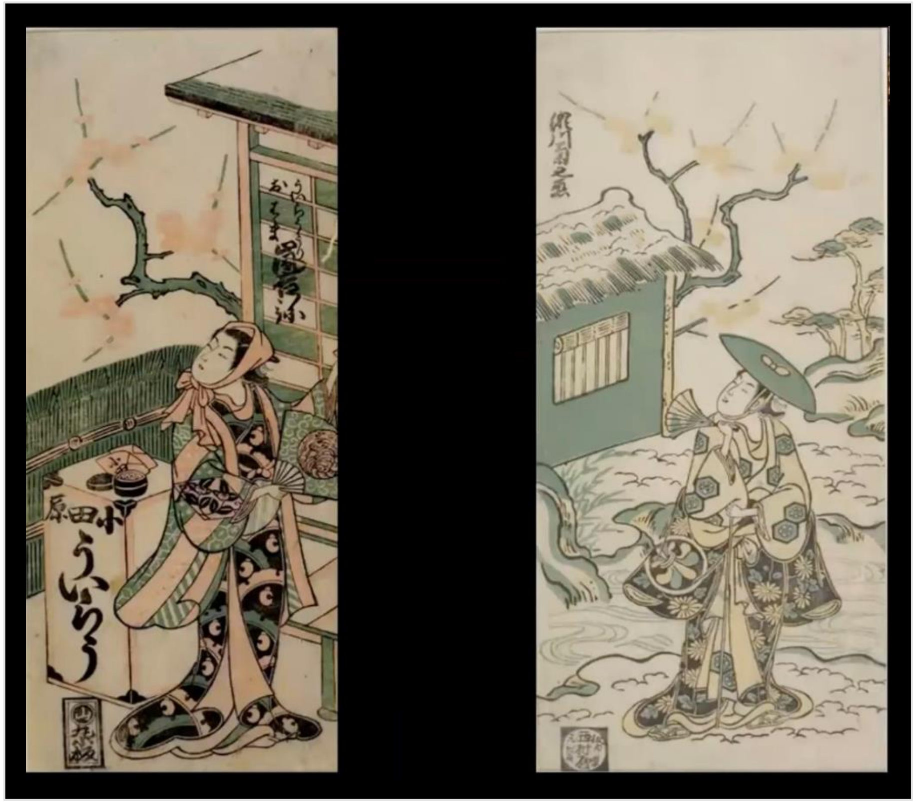


Infrared thermography of different lamps

Thermography image of CFL lamp vs incandescent lamp

Neutralize Damaging Light

LED sources significantly reduce damaging qualities of light such as UV and IR

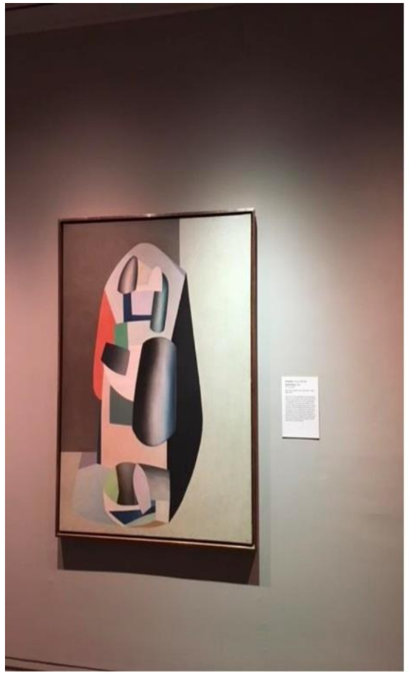


Example of faded safflower from the Harvard Library Print Collection

Side-by-side of similar light sensitive works with different durations of exposure.

Address Legacy Source Degradation

Return to the museum's high standard of quality lighting



Modern &
Contemporary

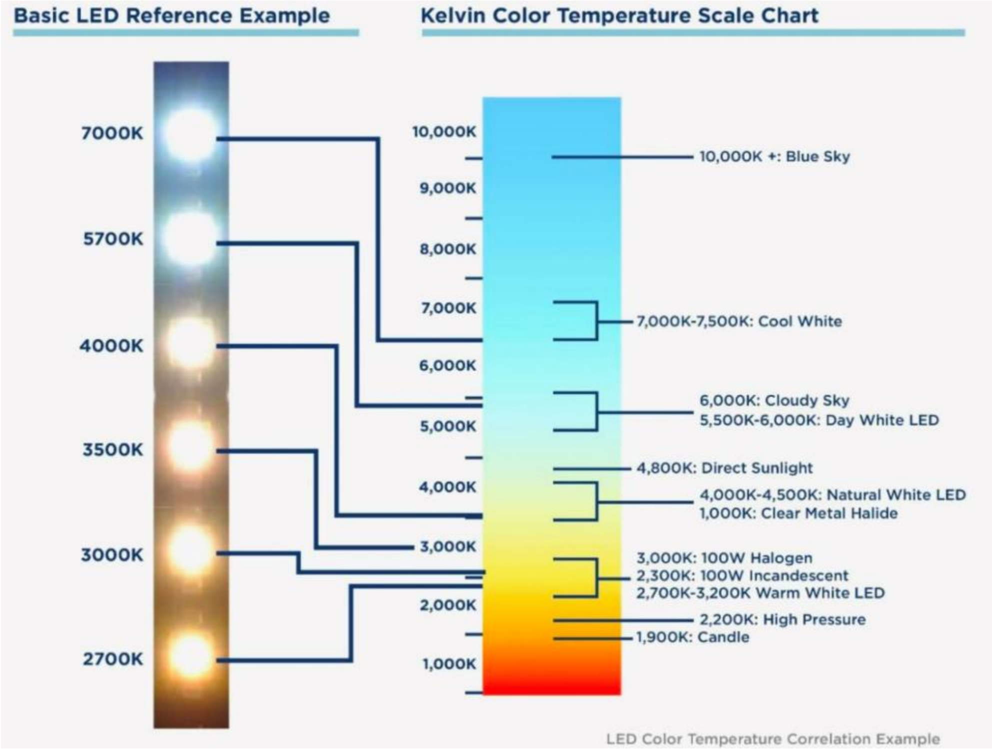
Asian Art

Greek & Roman

Baseline White Light

Standardize a Correlated Color Temperature of 3000K

Weber Galleries (G207, Asian Art)

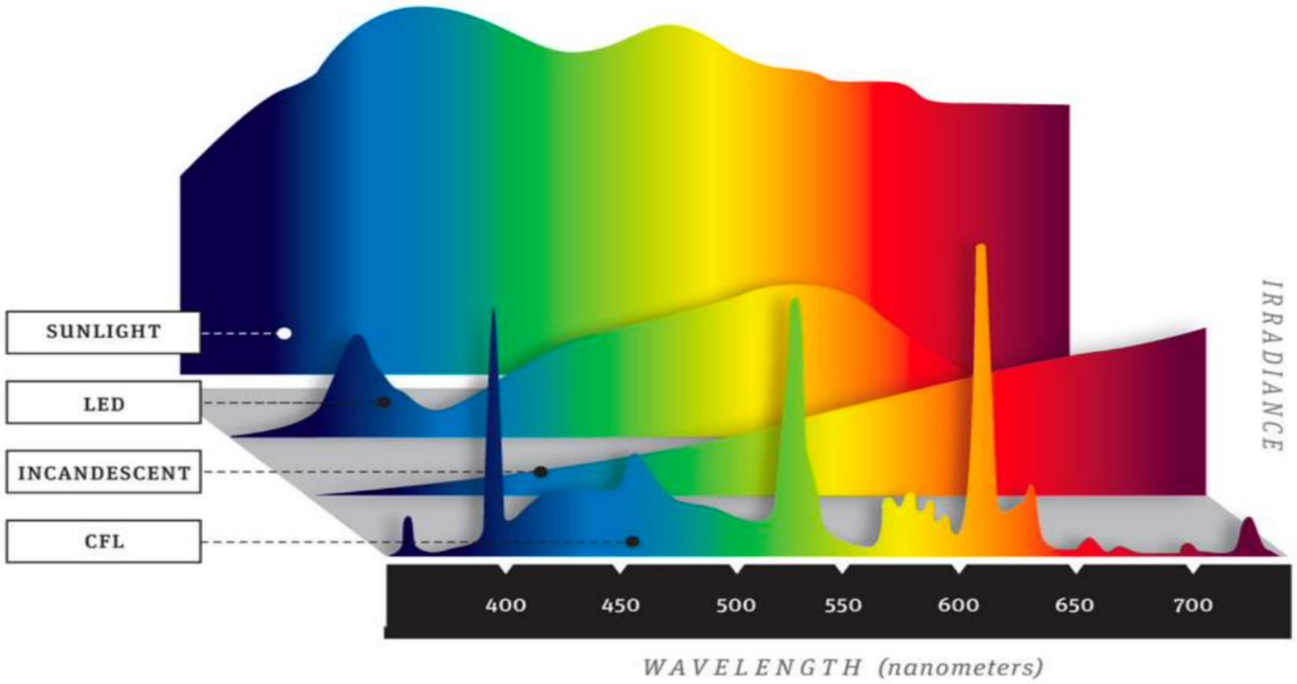


Correlated Color Temperature (CCT)

Quality Color Rendering

Establish a high Color Rendering Index (CRI)

Legacy source (left) versus LED (right)



Visible Light Spectrum

Improve Maintenance

Minimal equipment field maintenance translates directly to savings via lowered materials and labor costs

End of Life

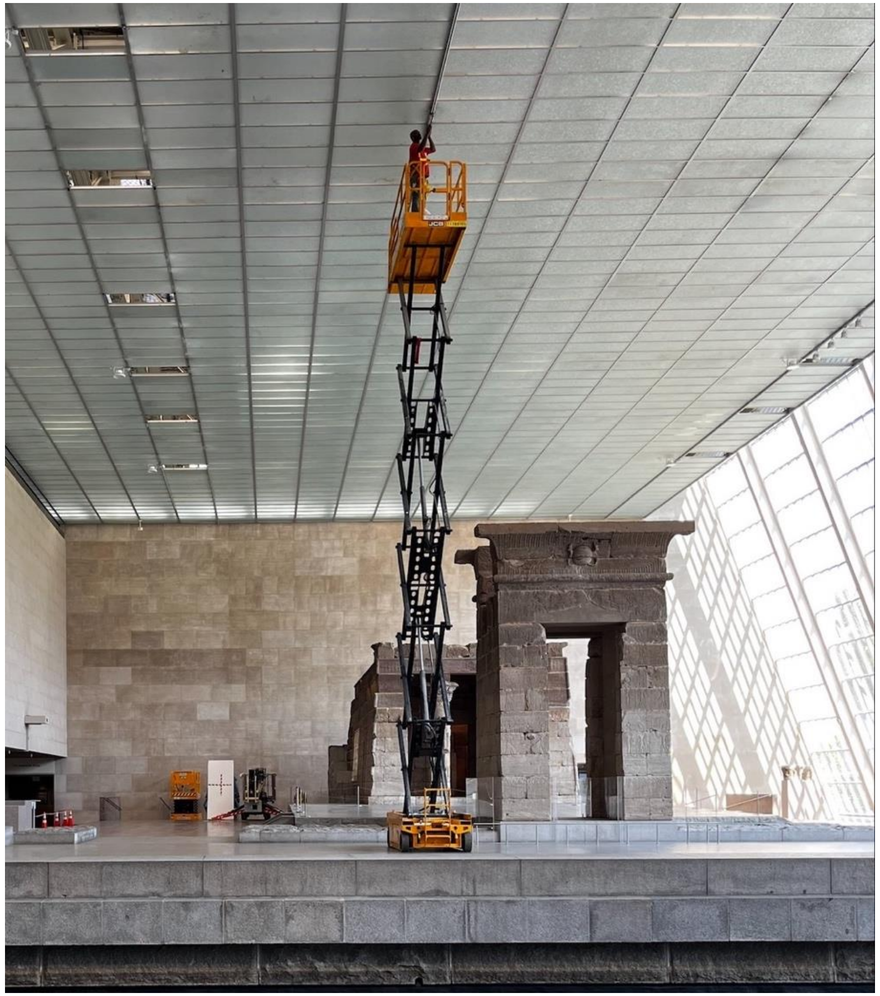
Relamped and focused

LED Upgrade in Progress

Legacy Source

Integral LED Source

Temple of Dendur Upgrade



In Progress

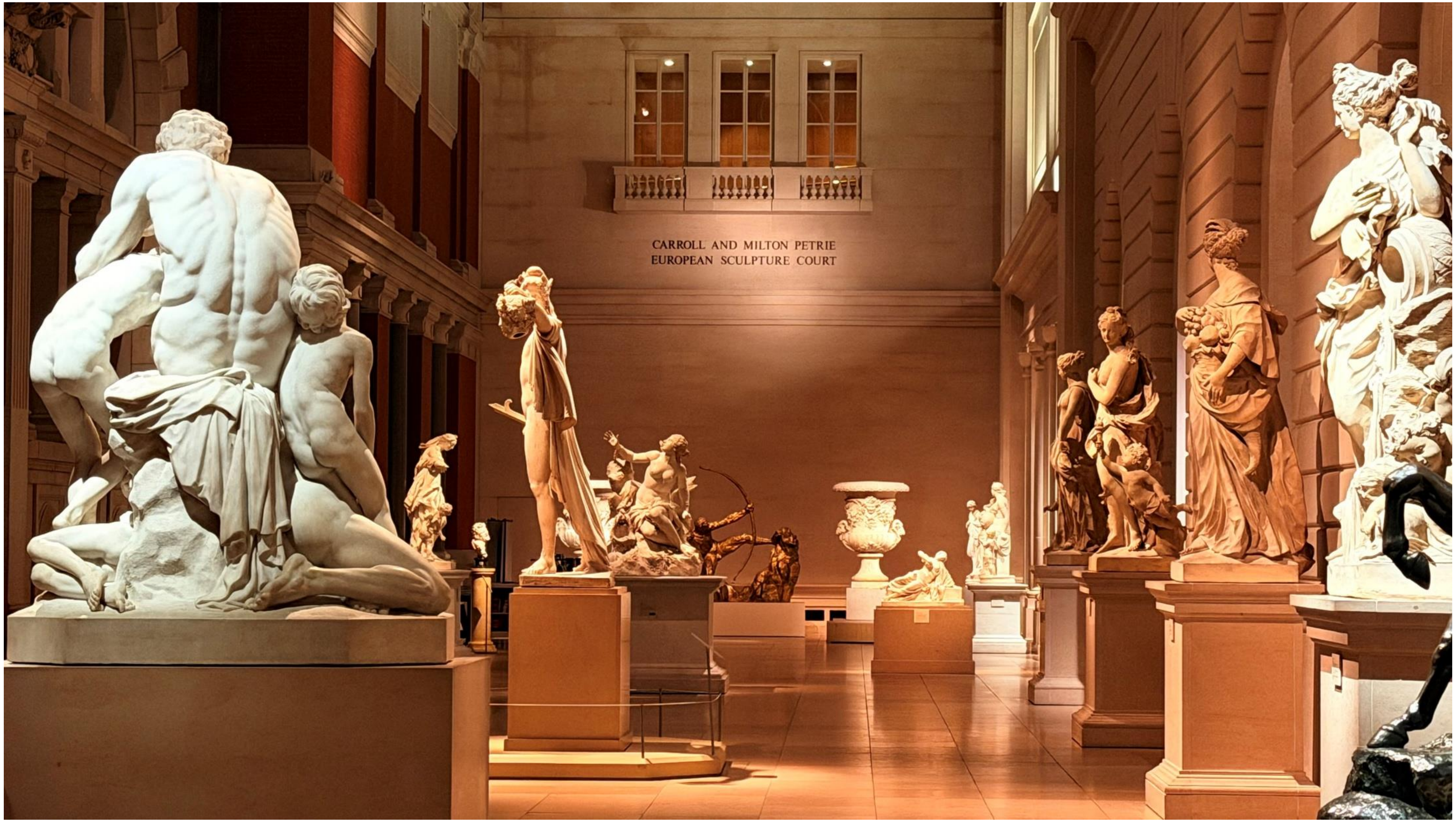
Complete

Wrightsman Period Room Upgrade

Before

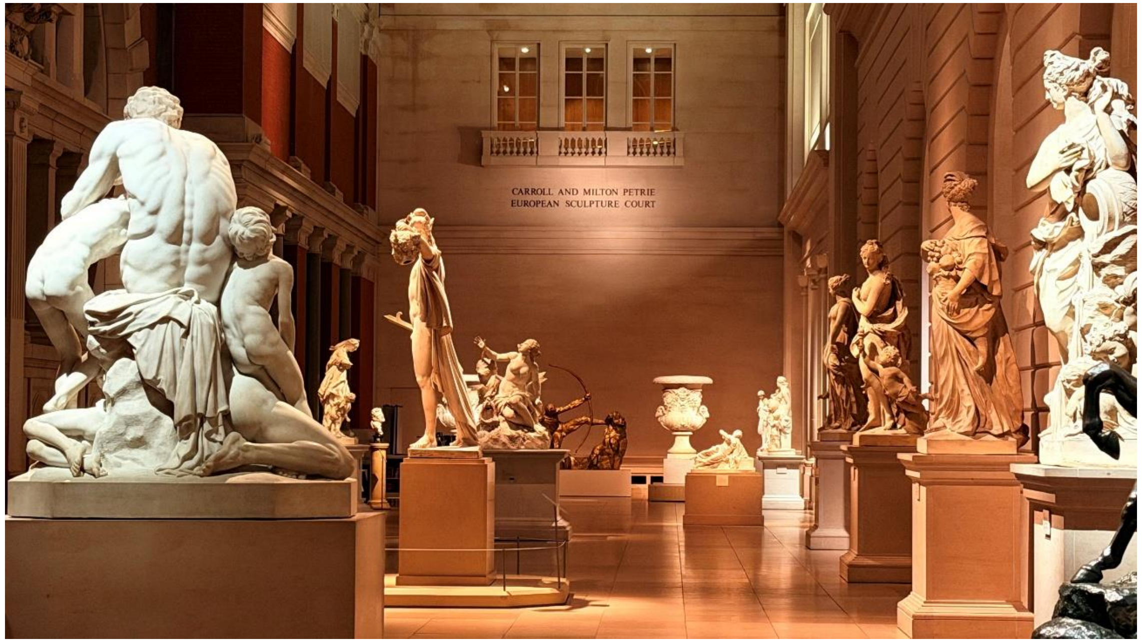
After

LED Upgrade in Progress



Petrie Court, 2026

THANK YOU!



Color Rendering

Color Rendering Index (CRI, R_a)

R_9

IES TM-30-2021 Color Metrics

R_f, R_g, $R_{cs, h1}$

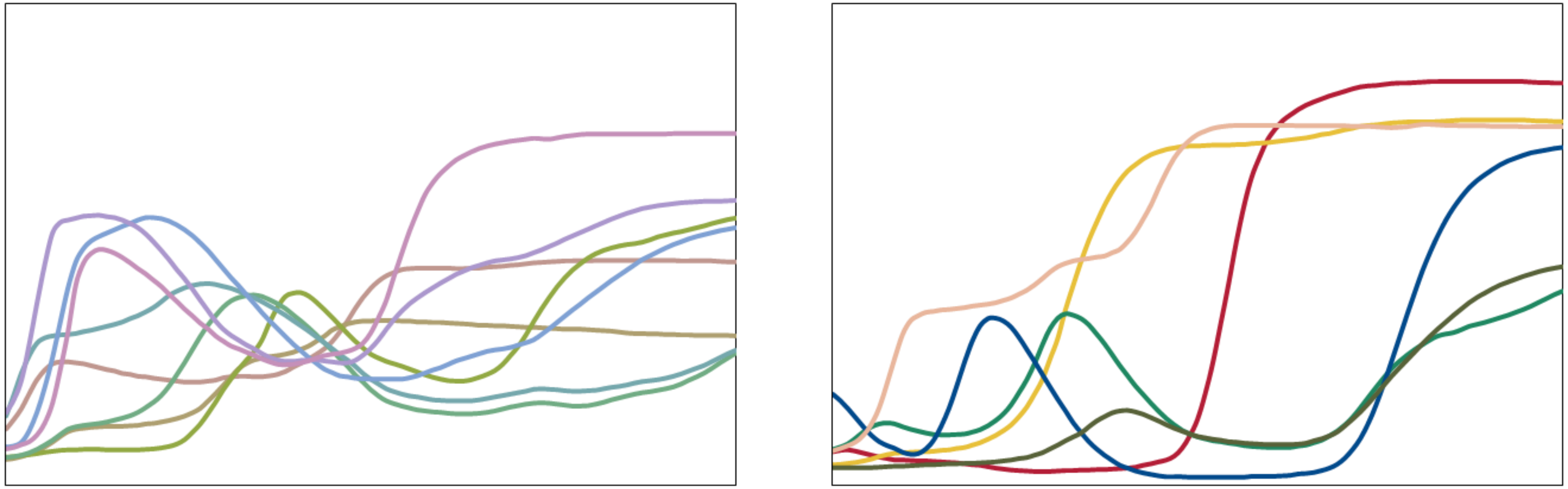
Color Rendering Index (CRI) Ra

The basics:

- Compares chromaticity of eight (pastel) test color samples under test illuminant to reference illuminant
- Intended to be a **fidelity** metric
- Reference is blackbody radiation (< 5000 K) or a representation of daylight (> 5000 K) at same CCT as test illuminant
- Averages (and scales) differences of each sample to result in single number
- Maximum score of 100 if all samples match exactly
- CRI is part of a larger system that includes 14 (now 15) total samples
- Applicable to sources near blackbody locus

CRI (aka Ra): The methods behind the metric

eight color samples



Approximation of Color Samples for CRI Ra (3000 K Blackbody Radiation)

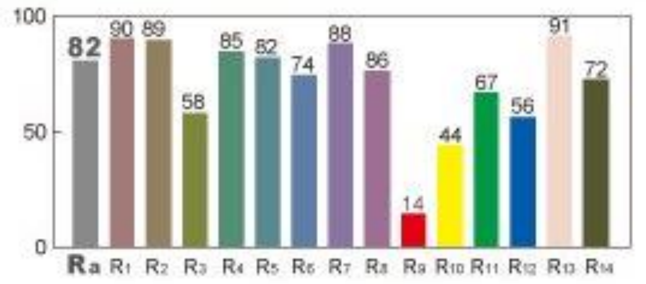
TCS 01 | TCS 02 | TCS 03 | TCS 04 | TCS 05 | TCS 06 | TCS 07 | TCS 08

Color Samples for R_9–R_{14}

TCS 09 | TCS 10 | TCS 11 | TCS 12 | TCS 13 | TCS 14

Limitations of CRI

- Can be gamed by manufacturers to get higher scores
- Doesn't communicate color saturation
- Does not work well for very discrete SPDs (i.e., RGB LED)
- Red colors seem to get short-changed



Special Color Rendering Index R9

- Same calculation method as CRI (Ra)
- Saturated red
- Red is particularly important for human skin complexion
- Often considered a valuable supplement to CRI (Ra)

Because color space is skewed at red…
R9=0+ is Good; R9=50+ is Very Good; R9=75+ is Excellent

[Equivalent R9 CRI = 100 – (100-R9)/4]

IES TM-30-2021 Color Rendering Metrics Rf and Rg

- Recognition that one metric doesn't fit all needs
- A fidelity metric can't also convey preference and discrimination (both related to the degree of saturation)
- TM-30 two-metric system (fidelity [R_f] and gamut [R_g]*)*
- R_f quantifies *average* color rendition of 99 color evaluation samples (CES) selected to represent real objects uniformly distributed in color space, still related to the reference source
- R_f ranges from 0 to 100. Rf > 85 usually is very realistic in appearance
- R_g quantifies the average increase or decrease of color saturation. 100 means identical saturation to reference. Can range above and below 100. Rg above ~106 can indicate a cartoony-appearance. Below ~95 can indicate washed-out appearance.

IES TM-30-2021 Color Rendering Metric Rcs, h1

Examples of chroma shift in red (it tells you a LOT about vividness, dullness, naturalness

Desaturated
(e.g. $R_{cs,h1} \leq -10\%$)

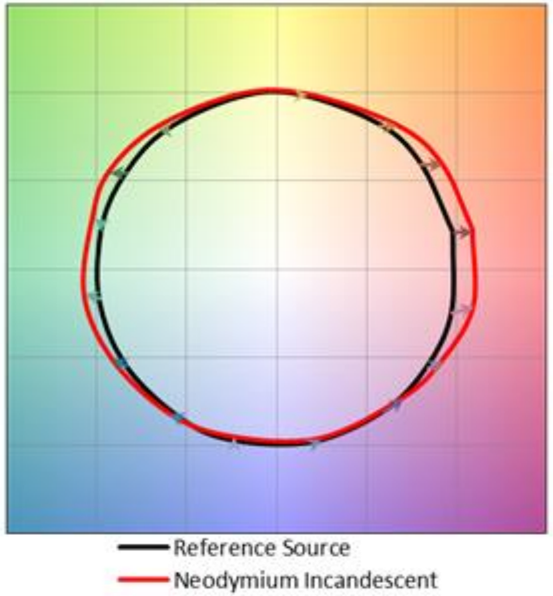
Normal saturation
(e.g. $R_{cs,h1} = 0\%$)
Read, "chroma shift of hue angle bin 1 = 0%"

Highly saturated
(e.g. $R_{cs,h1} \geq +10\%$)

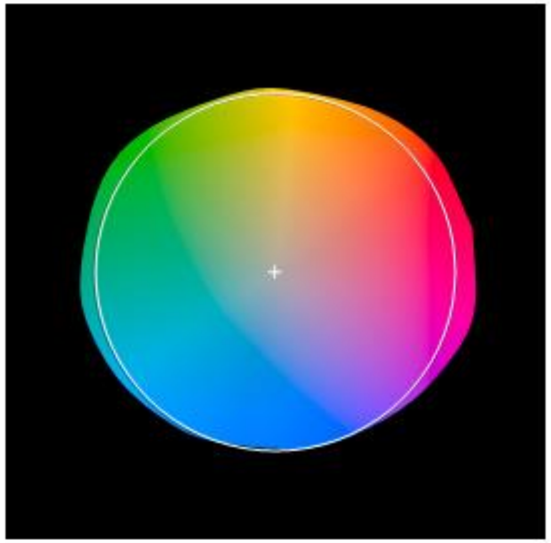
TM-30-2021 Color Rendering Metrics Graphics

- TM-30 two-metric system (fidelity [$\boldsymbol{R_f}$] and gamut [$\boldsymbol{R_g}$])
- Includes a spreadsheet tool with helpful color distortion graphics for better understanding rendition of specific hues.

Color Vector Graphic



Color Distortion Graphic



(Neodymium tungsten halogen Ra is 77, Rf is 86, and Rg is 109)

Advantages/Disadvantages of of CRI and TM-30 as metrics

- CRI is easier to understand, but it does not provide as much information as the professional needs
- TM-30 is more complex to use, but much more precise and predictive.

The Hunt Effect and how to overcome it

- Under low light levels (<50 lux or 3 cd/m^2) cones transmit less color information. Colors appear less vivid and true.
- Light sources with greater color gamut, can compensate for this.
- In some sensitive displays (e.g. watercolors, costumes), this may be appropriate

Conclusions + Notes

- If color rendering is a critical issue, consider more than just CRI
- Metrics are a good start, but if you are a designer, you must *evaluate color with your own eyes*.
- Standardized photometry should include SPD, CRI, CCT and Duv, Ra, and now Rf and Rg. (With the SPD file, you can calculate a large range of metrics.)

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Temporal Light Modulation ("flicker")

Almost all lighting products are now LED

- Many LED products ***ARE*** acceptable in terms of TLM
- Too many ***AREN'T***, and they include:
  - Holiday light strings
  - Ceiling fan lights
  - Color tunable strip lights and programmable bulbs
  - Recessed downlights using AC LEDs
  - Sparkly lights in chandeliers and sconces
  - Step lights
  - Undercabinet ltg, cove ltg, in-cabinet ltg, puck lights…
  - Some retrofit lamps, especially those with clear filament-type appearance
  - Most Type B TLED replacements for fluorescent







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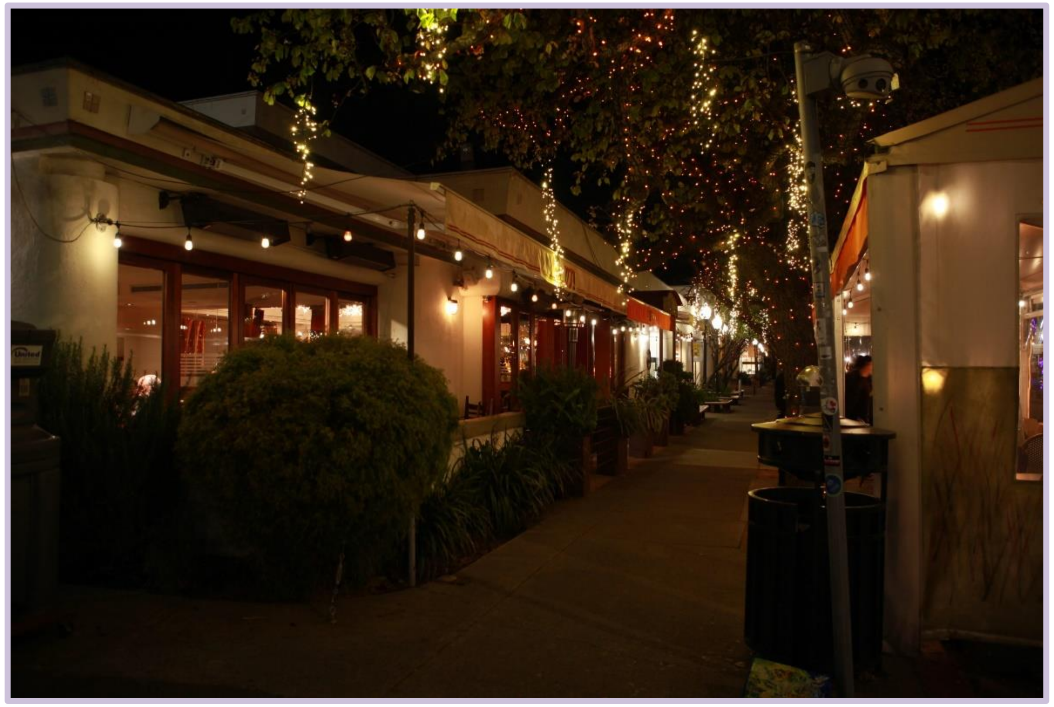
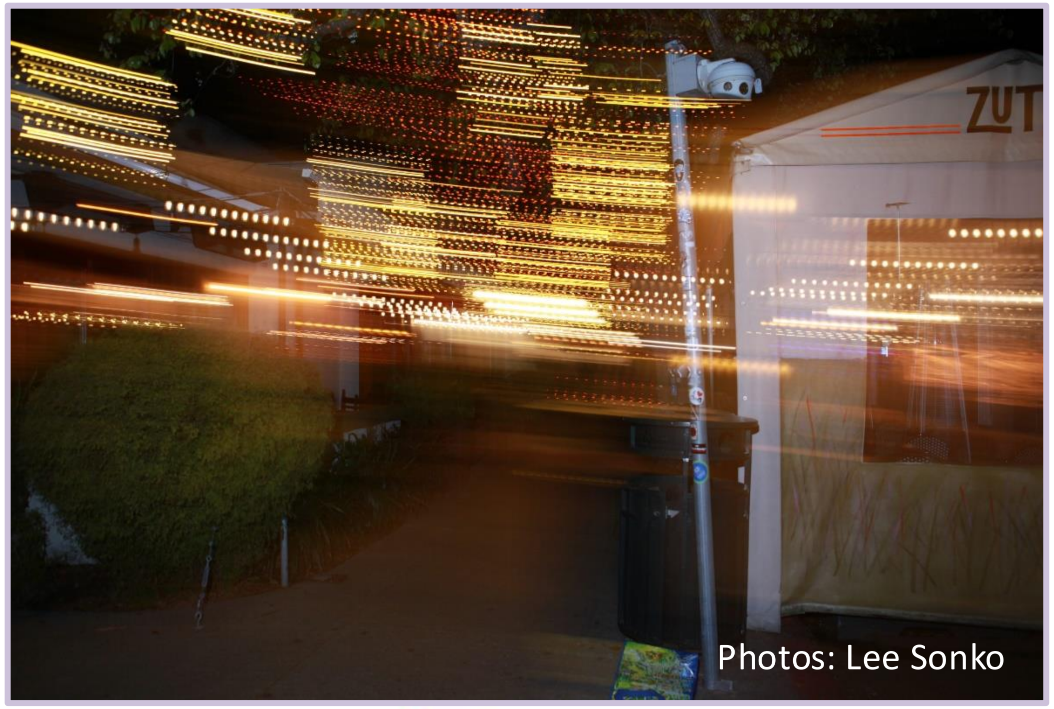
What is causing the flicker?

- LEDs have little luminous persistence over time
- Poor drivers (or no drivers at all)
- PWM dimming techniques
- No room in the fixture or lamp for better quality electronics
- Cost pressures for manufacturers
- **Many people don't *see* flicker or realize it's a serious problem for others (It's hard to care about a problem one cannot see)**





Photos: Lee Sonko

Demonstration of Temporal Light Modulation (TLM)

Direct Flicker
6 – 80 Hz
Direct view of modulating light source. Can trigger photosensitive epilepsy

Stroboscopic Effect
80 – 1000 Hz
Visible when there is a moving object (or body movement) lit by modulating light

Phantom Array Effect
80 – 20,000 Hz
Results from interaction of modulating light source and scanning view (large eye saccades)

Why do we care about Flicker (um, I mean TLM)?

Health and comfort-related responses to TLM by some observers:

This encompasses visual and *non-visual* responses (e.g., cognitive, behavioral, physiological, and psychological), including

- Headaches
- Migraines
- Seizures (primarily 3-65 Hz frequencies)
- Slowed reading, comprehension, etc.
- Distraction, disorientation
- Nausea

And, how about cameras??

How many people are affected?

Based on 2024 PNNL flicker experiment

~26% had adverse reactions (weighted for migraineur prevalence in population)

~45% reported being bothered by flicker

Health.com

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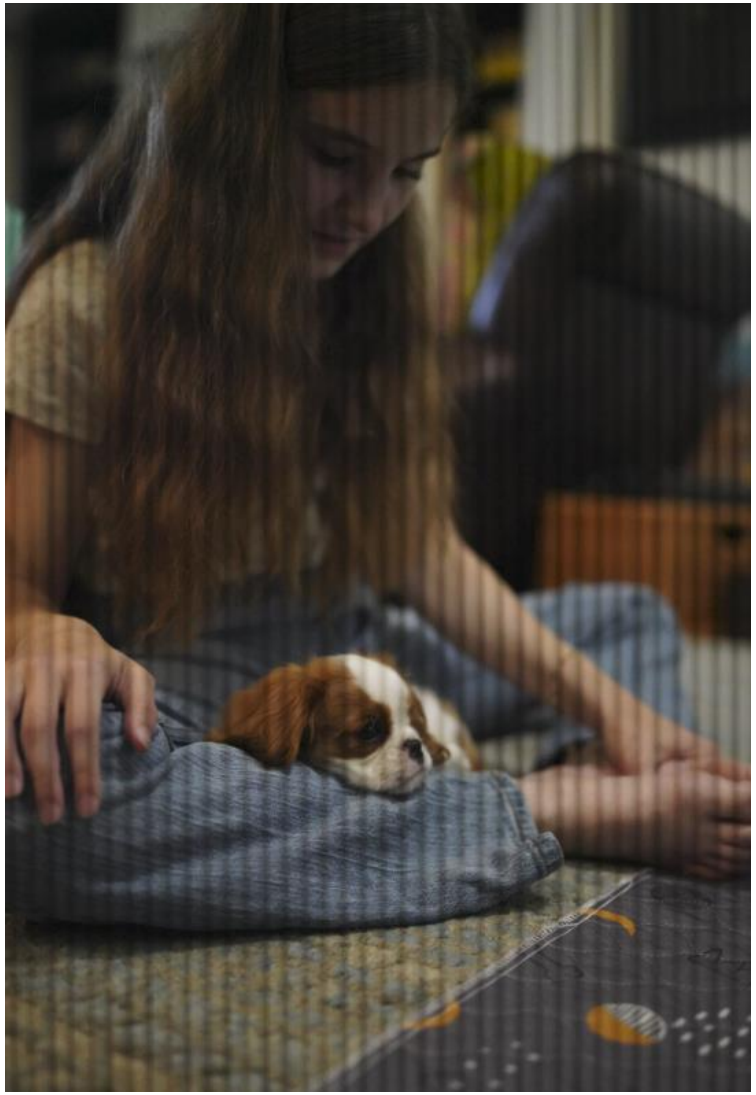

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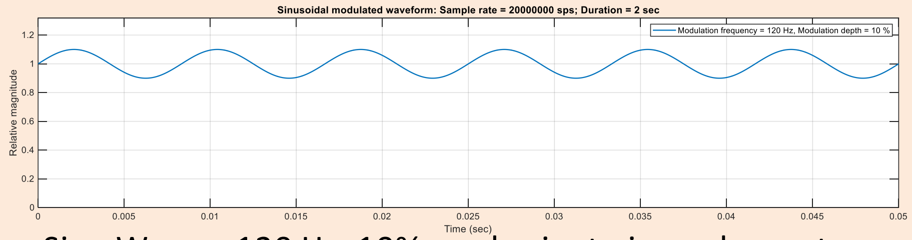
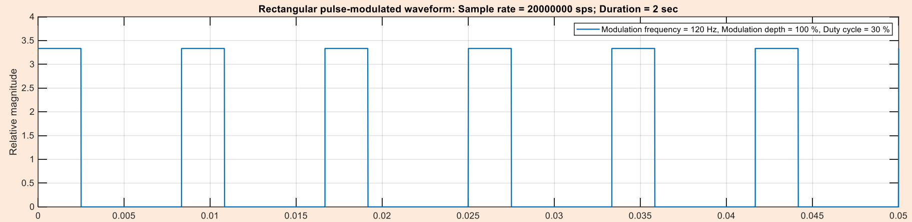
What affects TLM visibility?

Factors that affect the visual perception

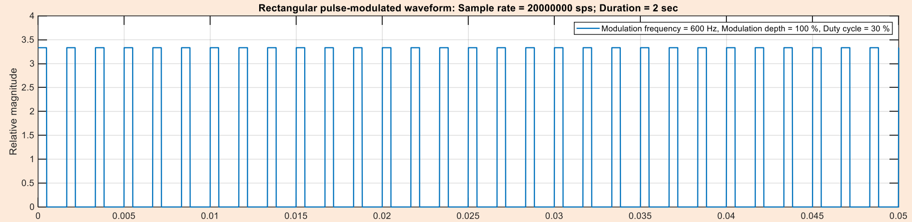
- Waveform shape (such as sine vs. rectangular waves)
- Modulation depth (also called % flicker, % modulation)
- Frequency
- Duty cycle
- Viewing conditions (size/contrast/edge, etc.)
- ***Sensitivity and characteristics of the observer (age, migraine people, those with brain injury, albinism, photosensitivity…)***



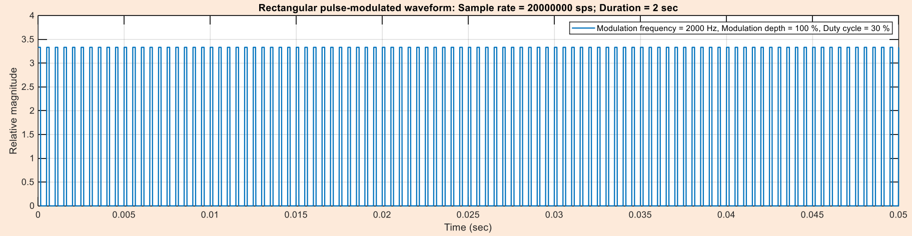
Sine Wave – 120 Hz, 10% mod., sim to incandescent



Rect. Wave – 120 Hz, 100% mod., 30% duty cycle

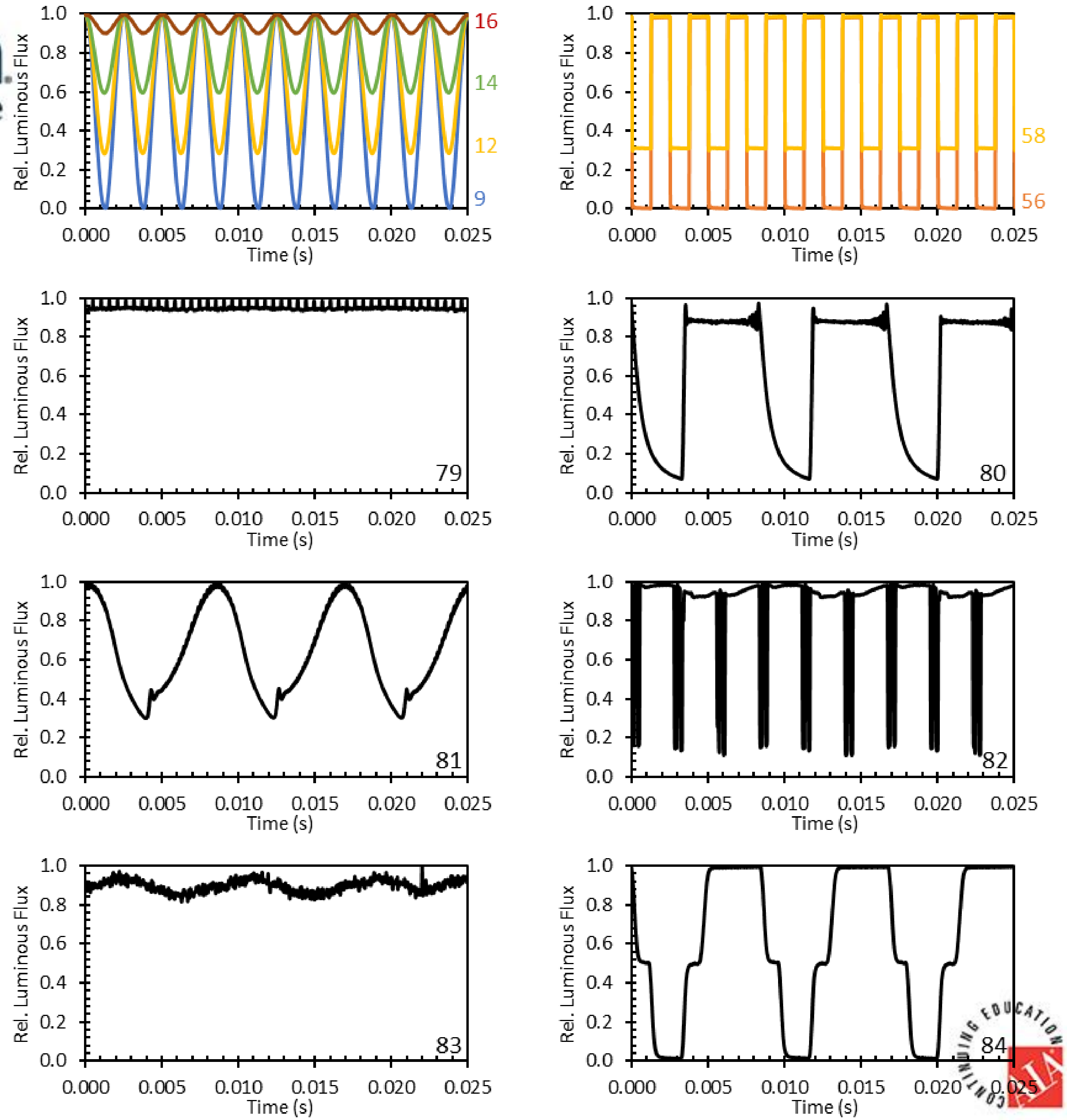


Rect. Wave – 600 Hz, 100% mod., 30% duty cycle



Rect. Wave – 2000 Hz, 100% mod., 30% duty cycle

TLM waveforms from LEDs can look like almost anything!



TLM Guidelines for interior applications ARE AVAILABLE!

ANSI/IES TM-39-25:
Quantification and Specification of Visual Responses to TLM

- Defines terms, summarizes research, describes metrics:
  - Flicker Perception Metric (M_P) [DVFM]
  - Stroboscopic Visibility Measure (SVM)
  - Phantom Array Visibility Measure (PAVM)
- Provides provisional Minimum – Good – Better categories based on TLM effect and target metric values
- IES Testing Procedures Committee LM-90 subcommittee also updating their measurement guidelines
- IES Vision Science Committee working on another TM to formalize all the steps of calculations for DFVM, SVM, PAVM

IES TM-39: Quantification and Specification of Flicker

- Contains provisional guidelines for interior applications
- 3 metrics; 3 target values; 3 quality levels – categorization based on worst level

	MINIMUM	GOOD	BETTER
Metric Method			
Direct Flicker	$M_p \leq 1.0$	$M_p \leq 0.9$	$M_p \leq 0.4$ For 6 Hz ≤ f ≤ 30 Hz, modulation ≤ 0.1%
Stroboscopic Effect	SVM ≤ 1.6	SVM ≤ 0.9	SVM ≤ 0.4
Phantom Array Effect	PAVM ≤ 1.6	PAVM ≤ 0.9	PAVM ≤ 0.4
Alternate Frequency Method			*f* ≥ 10,000 Hz for sinusoidal waveforms *f* ≥ 20,000 Hz all other or DC Waveform

How to avoid TLM (flicker) at this point in time:

- Specify products that produce steady output over time, very high frequency, and/or avoid PWM
- Test products in your own laboratories. Get a good flicker meter. Test at full range of operation on dimmer, and also test for color at low end. 2000 Hz is *not* high enough frequency for PWM.
- If possible, size the LED system for the application. Don't use 10W LED systems that are always used at <1W, for example. Or, use >20 kHz drivers, so that PWM is not an issue even at low levels.
- Sample specification:

> Combination of power supply and dimmer shall deliver current to the LED that meets IES TM-39 criteria for BETTER performance. Alternatively, driver shall use constant current reduction (CCR) to reduce light output to 1% of max output without color shift; or, if dimmer/driver combination uses PWM, output frequency shall meet or exceed 20 kHz.

- Talk to your reps and suppliers. Raise awareness.

Interview format, MC interviews Amy & Naomi

M: A, what are the big problems today, as you grapple with the challenges stated in the abstract?
(during our telecons/meetings we've talked about these factors)
Color, heat, flicker, OAD track fittings, limits, dimming required on board, standards & lack thereof, energy & labor costs, jobs preservation, retraining,
M: N, how did you become aware of these issues & how were you able to respond?
Energy concerns: switch to leds was unquestioned; Utility rates were increasing; does this concern the museum? environmental stewardship nypa lessons learned;
M: N, does TM30 provide any insight or useful information related to these issues & the vast needs of museum lighting? (maintain illuminance > low light but need color constancy > color spectrum through dimming)
heat> conservation> drivers heat require ventilation > HVAC demand?
Does the mfr state heat ? drivers generate heat. High frq drivers = lower pwr draw > receiver
Increase efficiency? (check driver/fixture spec sheerts for pwr draw).
Funded by utilities; testing independent; standards?
M: A, did the pause during the pandemic have any impact on your project? How did you map the process to move forward?
Were your suppliers aware of any of these issues prior to your RFI's? Have they been able to provide new tools, software, support specifically for this process? (or what specifically would you like/need from them? How can they help?)

Props/graphics

Flicker generator/wheel > wave forms

This concludes The American Institute of Architects Continuing Education Systems Course

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