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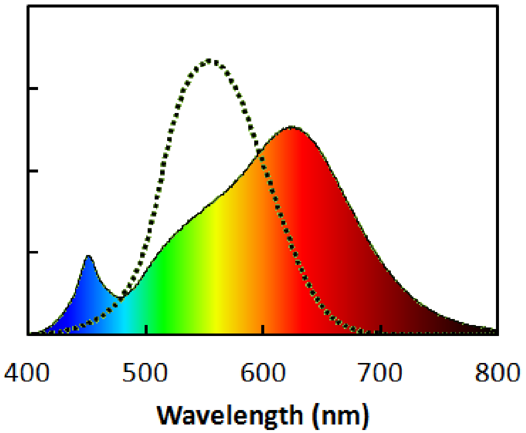
Narrow-band Spectra and Optics – Opportunities and Challenges

Paul Fini 11/8/17

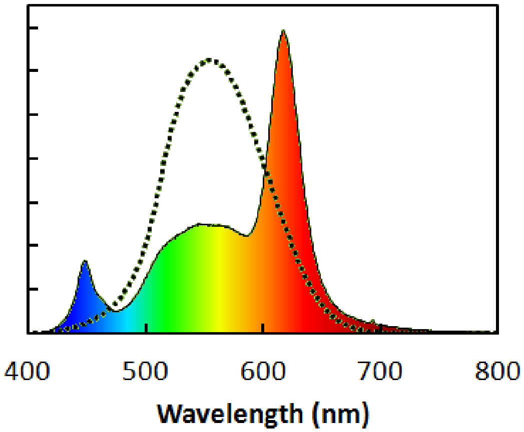
Narrow-Band Spectra – High Efficacy

- Conventional all-phosphor spectra: **broad red emission** with long-red/near-IR tail
- Narrow (<35nm) red peak increases spectral efficiency by **10-20%**
- Red direct **emitters** and **narrow-band downconverters**: spectral efficiency w/ differing tradeoffs.

Conventional phosphors



Green phosphor + red NBD

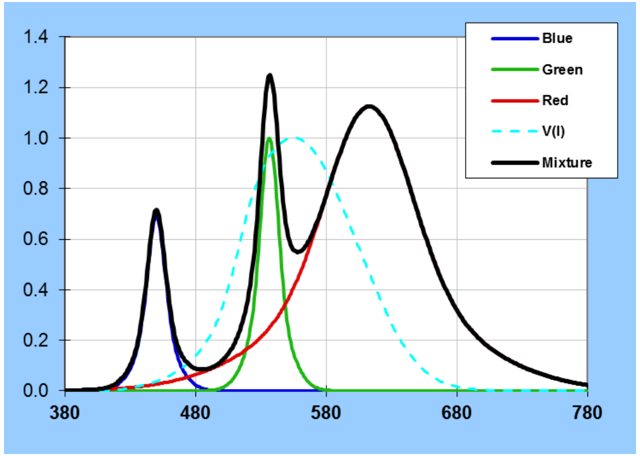


Characteristic	Red LEDs	Red NBDs
Peak Width	~15-20nm	~30-40nm
Thermal Droop (output 25→85°C)	25-35%	<5%
System Color Mixing Impact	High	Low
Color Quality	Good	Good

➢ ***Narrow-band red emission is valuable for high color quality at high efficacy, but may introduce system-level tradeoffs.***

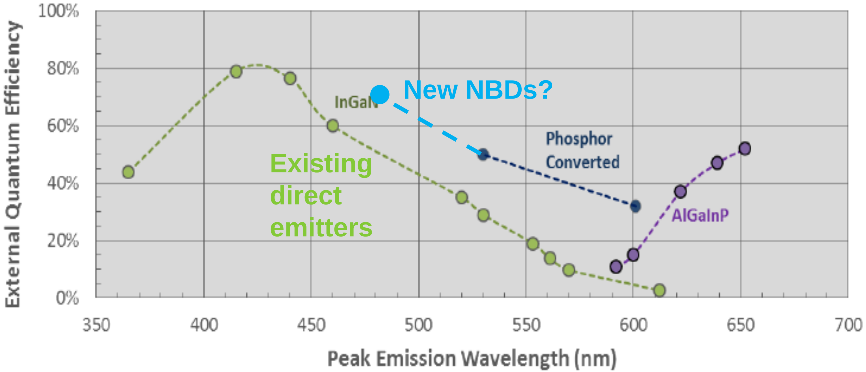
What About Narrow Green?

- **Efficacy benefit**: minimal compared to conventional green & red phosphors



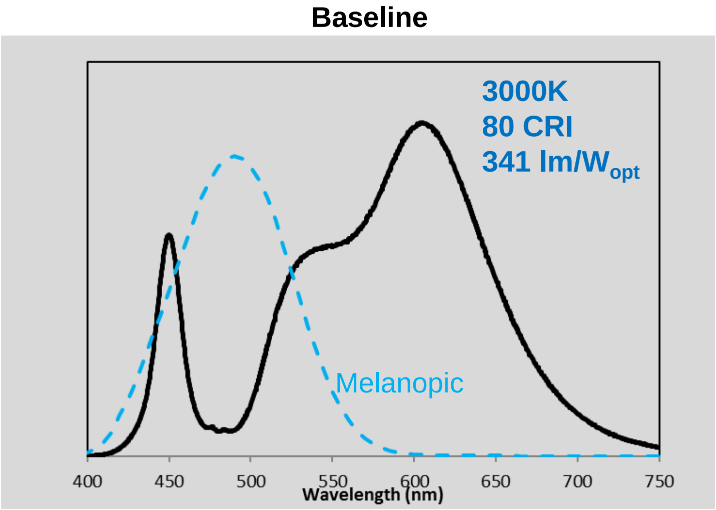
- Peaks are well within the eye response curve, thus **minimal** impact on efficacy (lm/W) with broad red peak.
- Narrow green *and* narrow red bumps efficacy by 5-7%, but at what color quality cost?

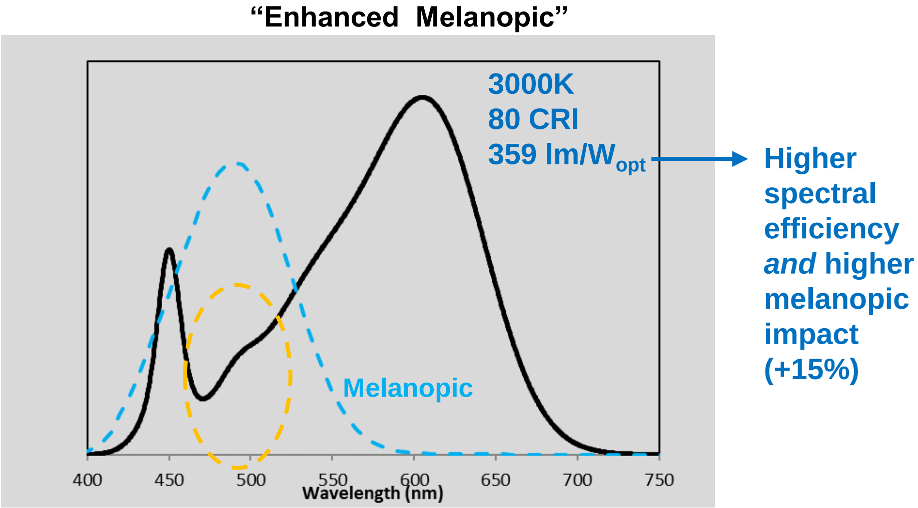
- Narrow green or cyan for emerging applications
  - **Cyan** NBDs (~480-500nm): melanopic impact
  - For >82% QY: higher EQE than direct cyan (~50%)



Spectral Engineering Beyond Efficacy

- Tailored narrow-band spectra may enable beneficial **physiological** or **psychological** responses.
- Example: spectra with “low” and “high” impact on melanopic eye response (cyan curve)



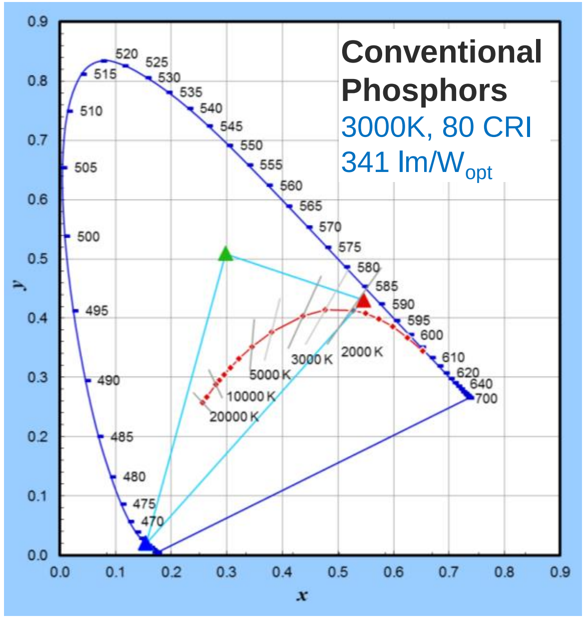


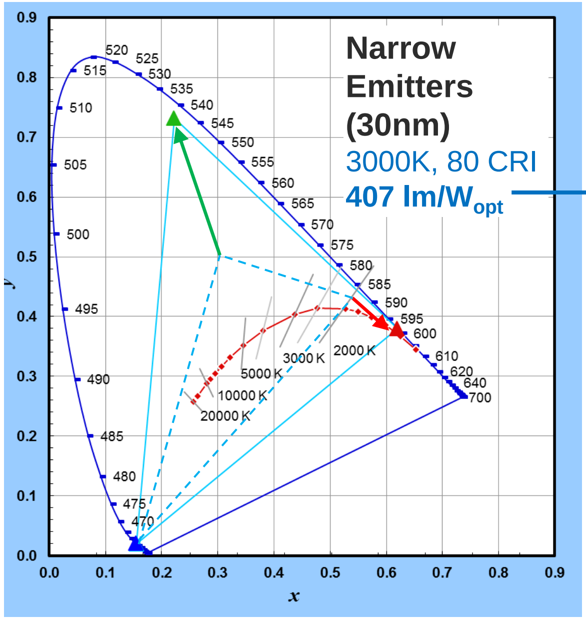
- **Opportunity:** define metrics such as “melanopic/W” while evaluating impact on lm/W, lux/W, & color quality.

➢ *New spectra will depend on the development of new **efficient** and **reliable** narrow-band (<40nm) emitters and downconverters from **cyan through red**.*

Narrow-band Spectra – High-gamut Color Tuning

- Narrow emitters enable a wider **color tuning gamut**, with high spectral efficiency on or near the blackbody locus.





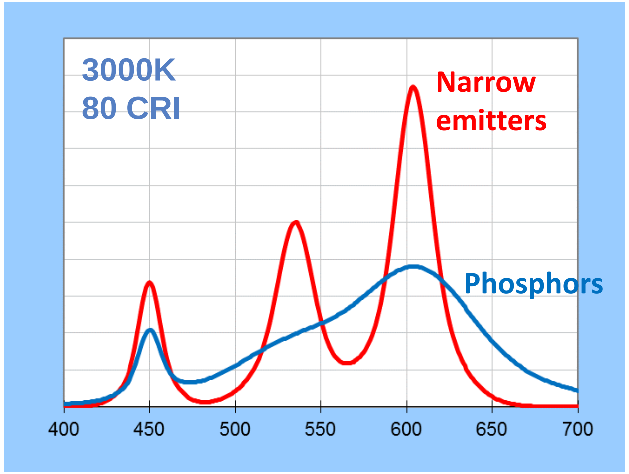
Higher spectral efficiency *and* higher gamut

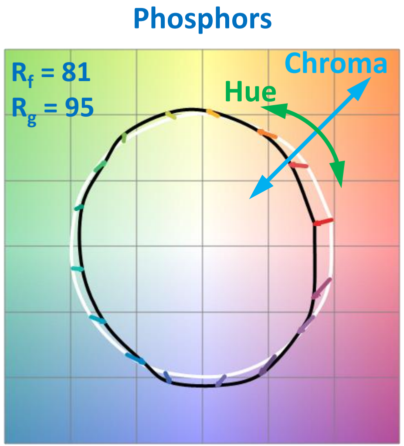
- **Challenges:**
  - **Color tuning:** requires investment in multi-driver control… this is now happening
  - Fixture-to-fixture **color consistency**: requires careful color point and intensity binning

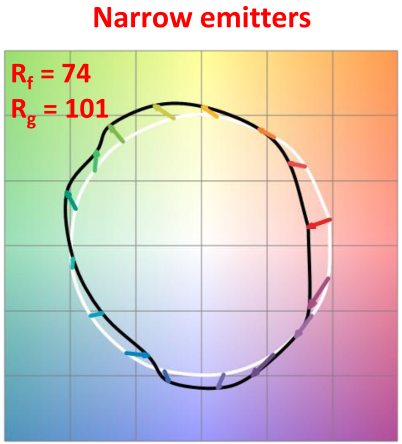
Color Quality – Beyond CRI

- So far spectra have been optimized for **CRI R_a** and **R_9.**

- **IES TM-30**: quantifies color qualities beyond fidelity
  - Fidelity metric **R_f** "penalizes" peaky/structured spectra
  - R_f can't be "gamed" as easily as CRI R_a
  - Gamut metric **R_g** quantifies averaged enhanced gamut**; $R_{cs,hj}$** sub-metrics tell *where* it's happening



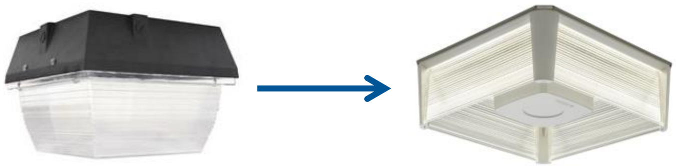




➢ ***Color quality measures beyond CRI R_a & R_9 should be assessed when specifying new spectra.***

Luminaire Optics: Present vs. Future

- SSL luminaire optics: designs evolving rapidly
  - Improvements via “non-legacy” form factors
  - Challenges still present in legacy form factors



- **Optical Efficiency**: 5-10% gains will be challenging

Note: these are ‘best case’, not average, efficiencies.

Properties and effiacies of white light production and direction by luminaire, then of use by end user	Units	Present	Future (Targets)			
		2015	2018	2020	2025	Goal
Driver efficiency	%	0.88	0.91	0.93	0.95	0.95
Package efficacy (at 25°C)	lm/W	137	175	208	237	255
Thermal efficiency droop	%	0.88	0.91	0.93	0.95	0.95
Fixture (optical) efficiency	%	0.90	0.92	0.94	0.95	0.95
Luminaire Efficacy of White Light Production/Direction	lm/W	95	133	169	203	218

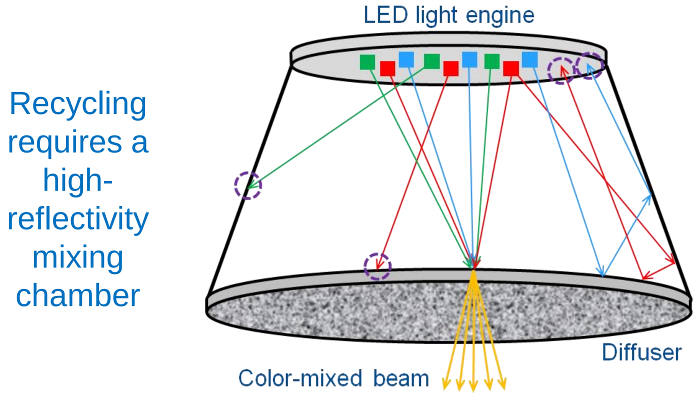
➢ ***Optical efficiency is just part of the equation!***

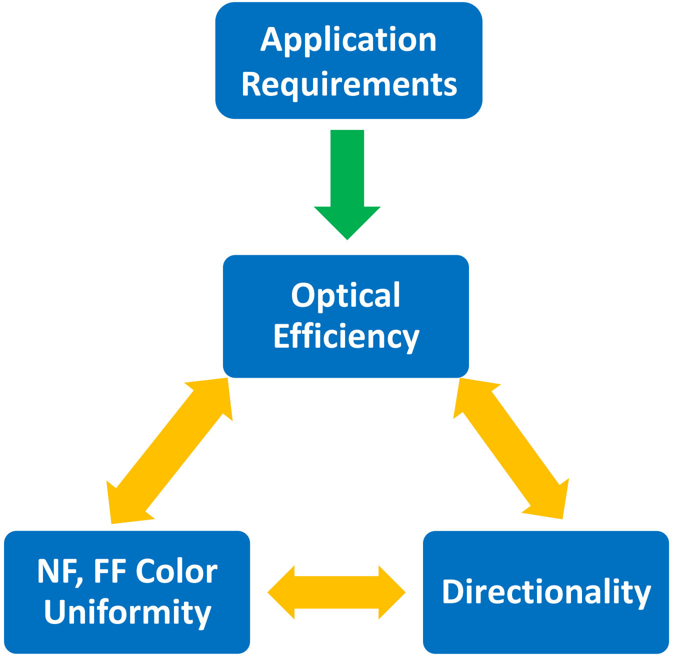
Illuminance & color uniformity, glare, utilization efficiency, & cost all matter.

System-level Color Mixing Tradeoffs

- **Discrete narrow emitters** require adequate color mixing prior to emission from the luminaire.

- **Challenges:**
  - **Color over angle**, particularly for **directional** emission
  - **Color mixing** at sufficient optical **efficiency**
  - Perceptible **near-field** (luminaire) color variation
  - Perceptible **far-field** (objects, surfaces) color variation



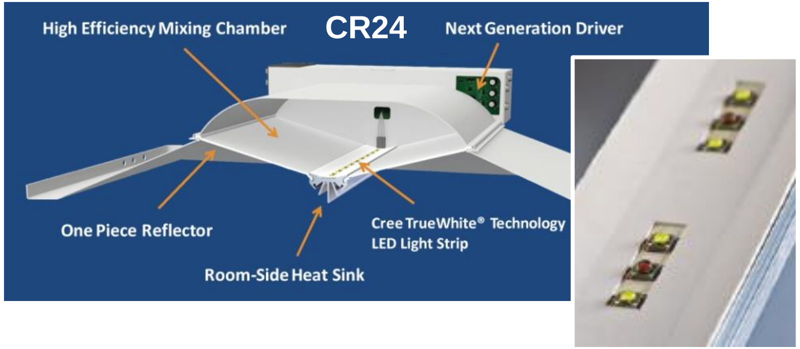


➢ *Achieving **efficiency, uniformity,** and **directionality** is a key challenge in SSL optical design.*

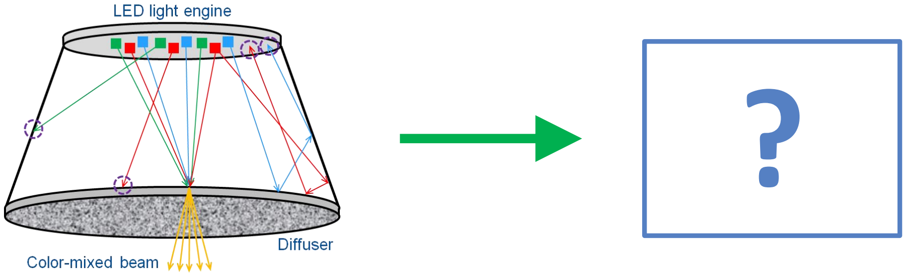
Color Mixing: Old vs. New School

- Opportunity: color mixing of **discrete emitters** for enhanced **efficacy** and **color point tuning**

- “Old School”: **mixing chambers** with diffusers
  - Largely limited to ~Lambertian emission
  - Needs very low absorption mixing chamber
  - Adequate size/shape needed

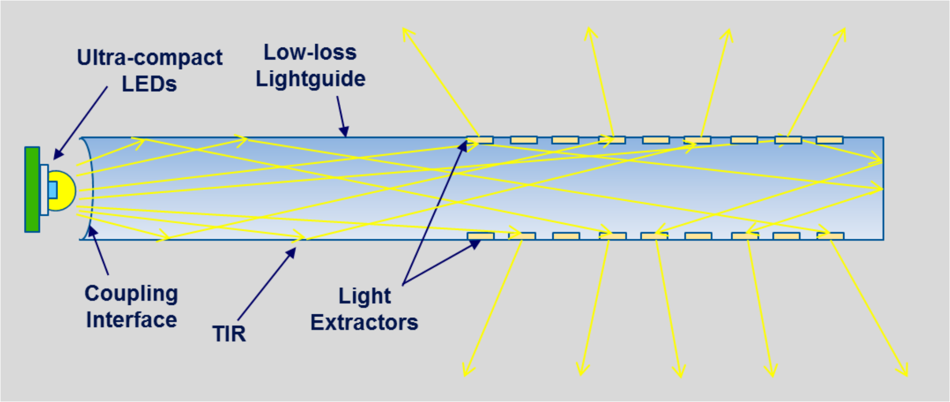


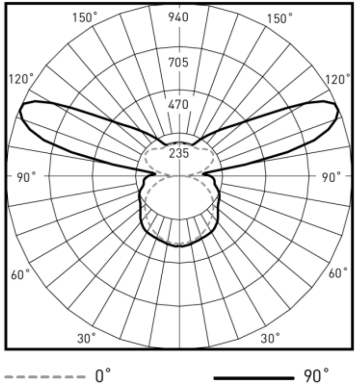
- “New School”: **refractive + light-guiding** optics?
  - Could rely (at least in part) on **lossless TIR**
  - Could enable **low-profile** form factors and **cost reduction**



New Optics Designs - Lightguides

- **Lightguides**: should effectively couple LED emission, convey light with little/no loss, and efficiently extract (not just scatter!) light



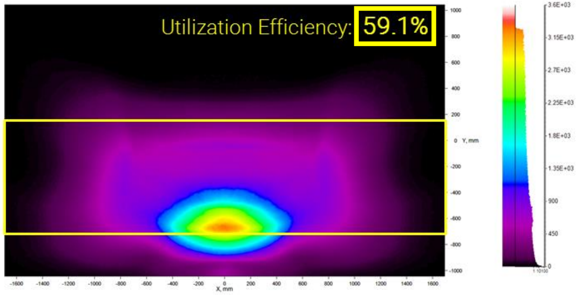


LN4: “asymmetrical to diffuse”
(using ceiling as optical element)

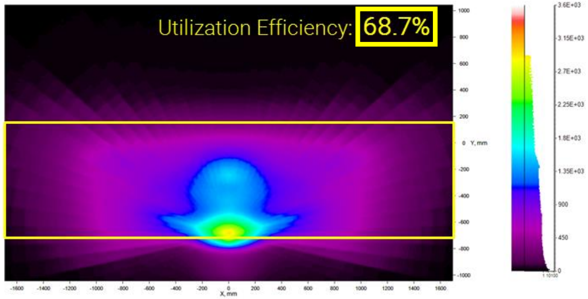
- **LEDs**: compact size & high luminance
- **Lightguide**: low bulk absorption, smooth surfaces, mechanically stable
- **Extractors**: maximize first-pass extraction

More Considerations: Utilization Efficiency, Glare

Utilization Efficiency:



vs.



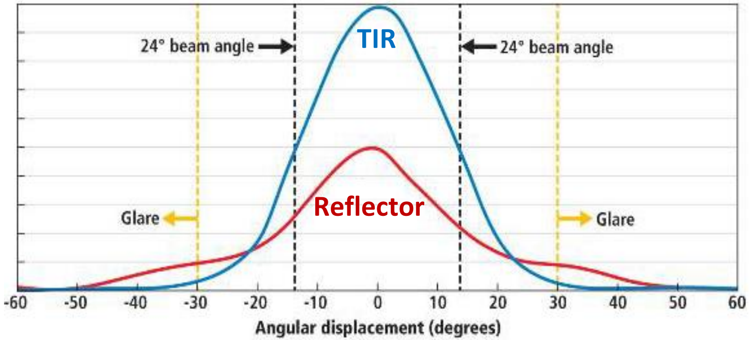
Outdoor: some distributions well defined by guidelines.

Indoor: lux level guidelines used, but distributions “TBD”

Opportunities for application-optimized optics

- Optical **trade-offs** requiring innovation:
  - **Low glare** vs. high **optical efficiency**
  - Far-field **illuminance** vs. **color** uniformity
  - **Aesthetic** vs. **functional/geometric** limitations

TIR optic had parity lm/W but ~2x lx/W *and* reduced (by ~4x) high-angle glare



After W. Jiang and Kevin Schneider, LEDs Magazine 2/12.

Summary

- **Narrow-band emitters** and **downconverters**: promising efficacy and application-optimized spectral gains

- **Efficacy**
  - *Opportunity*: superior spectral efficiency
  - *Challenge*: significant improvements needed in materials efficiency and reliability from cyan to red

- **Color quality**
  - *Opportunity*: application-optimized color quality
  - *Challenge*: controls for optimized performance *and* application values

- **Optics design**
  - *Opportunity*: new aesthetics, better light utilization & new application values
  - *Challenge*: mitigate tradeoffs among efficiency; color mixing; uniformity; glare; …

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