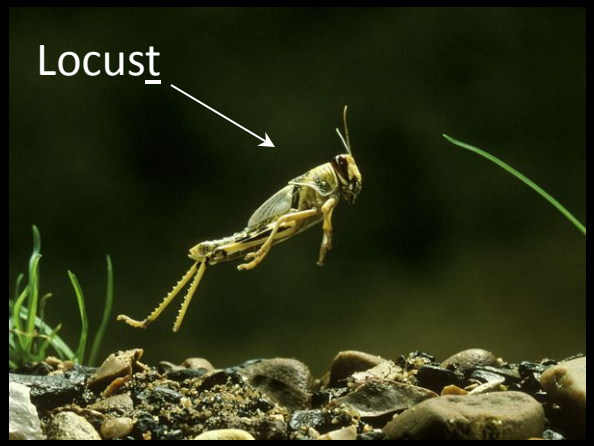
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Color Spaces and Planckian Loci: Understanding all those Crazy Color Metrics



Naomi J. Miller, FIALD, FIES
Michael Royer, PhD
Pacific Northwest National Laboratory
Portland, OR

What is COLOR?

for color scientists?

for building occupants?

for designers/specifiers?

COLOR…

- is one of the key attributes of lighting quality
- is rooted in human perception

COLOR METRICS…

- allow for communication of color attributes
- attempt to characterize human perception, but aren't always perfect
- have changed and improved over time

Halogen
99 CRI , 2917 K, D_{uv} 0.000

Metrics aren't perfect!

Compact Fluorescent
82 CRI, 2731 K, D_{uv} 0.003

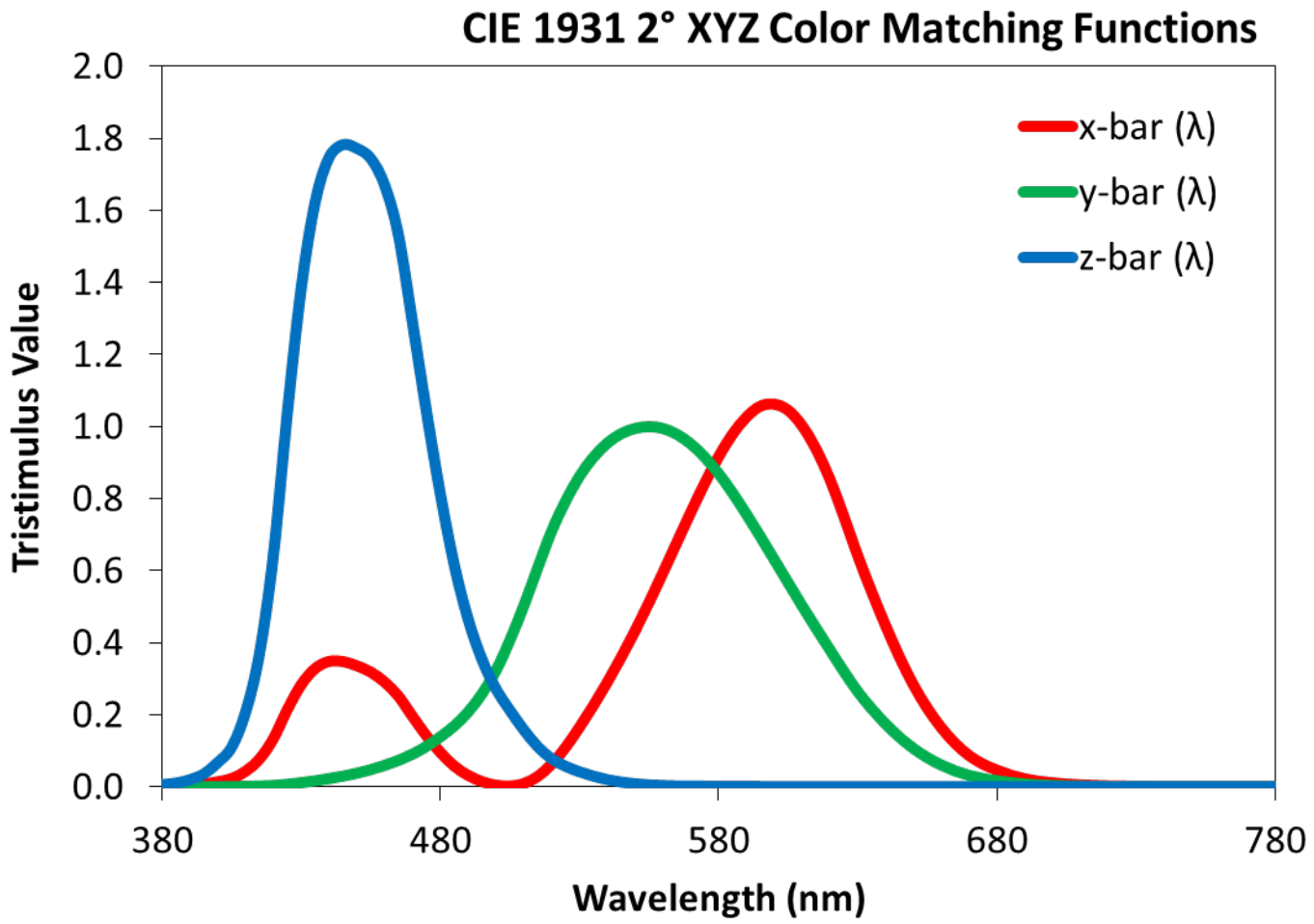
LED
84 CRI, 2881K , D_{uv} 0.000

Quantifying Color

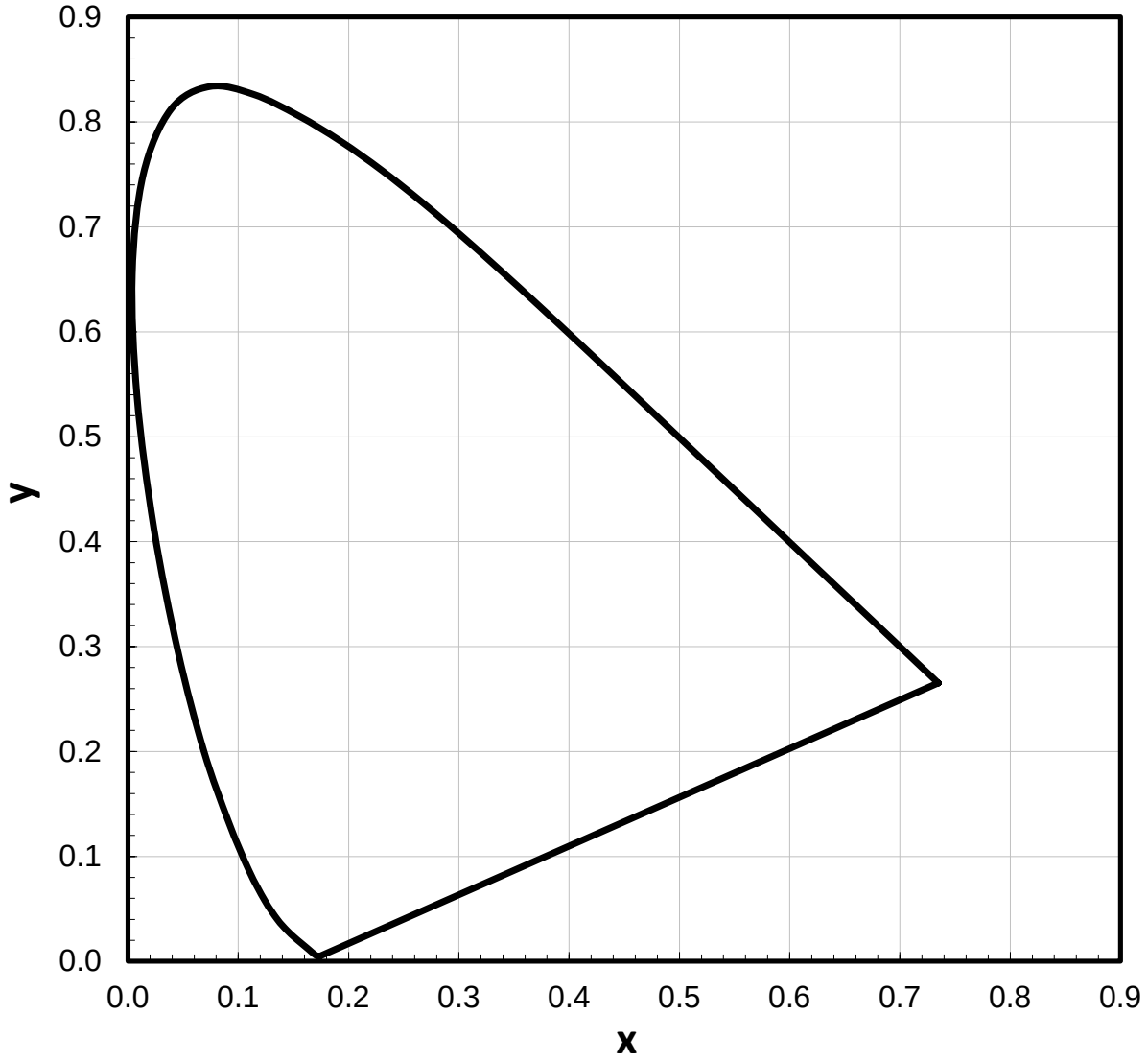
The CIE System of Colorimetry

Chromaticity Diagrams & Chromaticity Coordinates

Color Matching Functions (Transformed)



CIE 1931 (x, y) Chromaticity Diagram

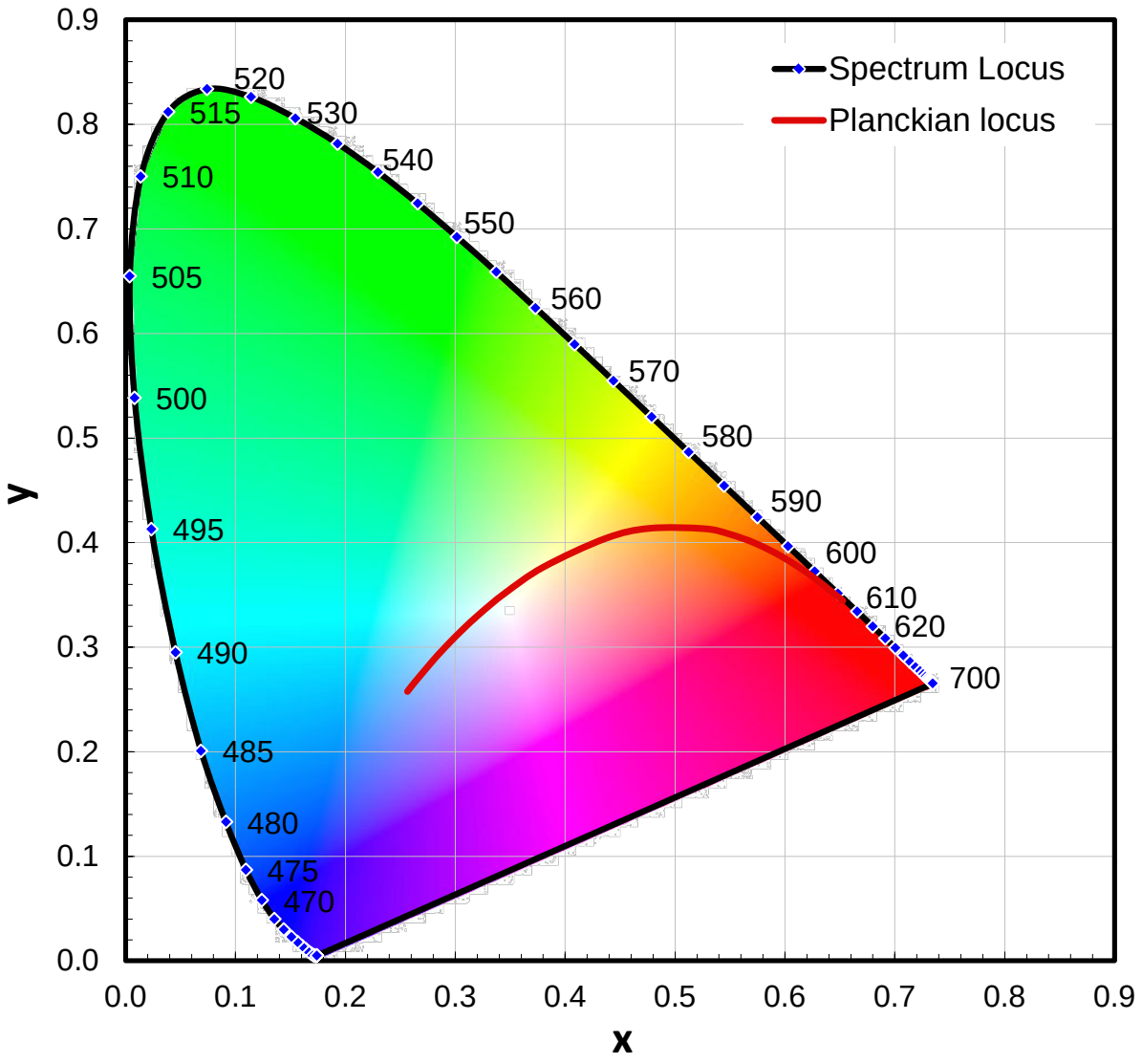


$$X = \int_0^\infty I(\lambda)\,\overline{x}(\lambda)\,d\lambda$$
$$Y = \int_0^\infty I(\lambda)\,\overline{y}(\lambda)\,d\lambda$$
$$Z = \int_0^\infty I(\lambda)\,\overline{z}(\lambda)\,d\lambda$$

x = X / (X + Y + Z)
y = Y / (X + Y + Z)

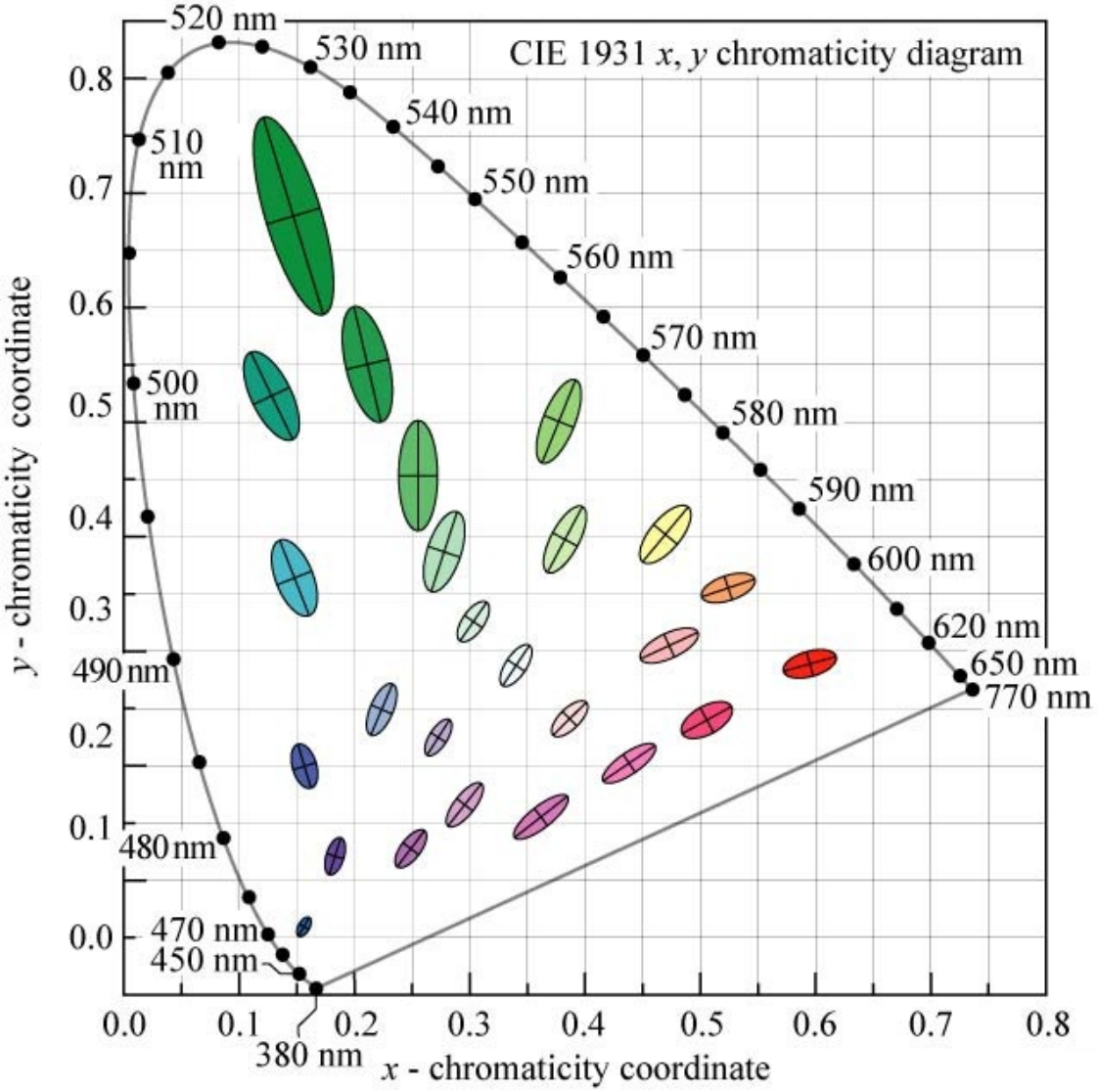
- x-y coordinates
- x + y + z =1
- Third dimension is lightness

CIE 1931 (x, y) Chromaticity Diagram



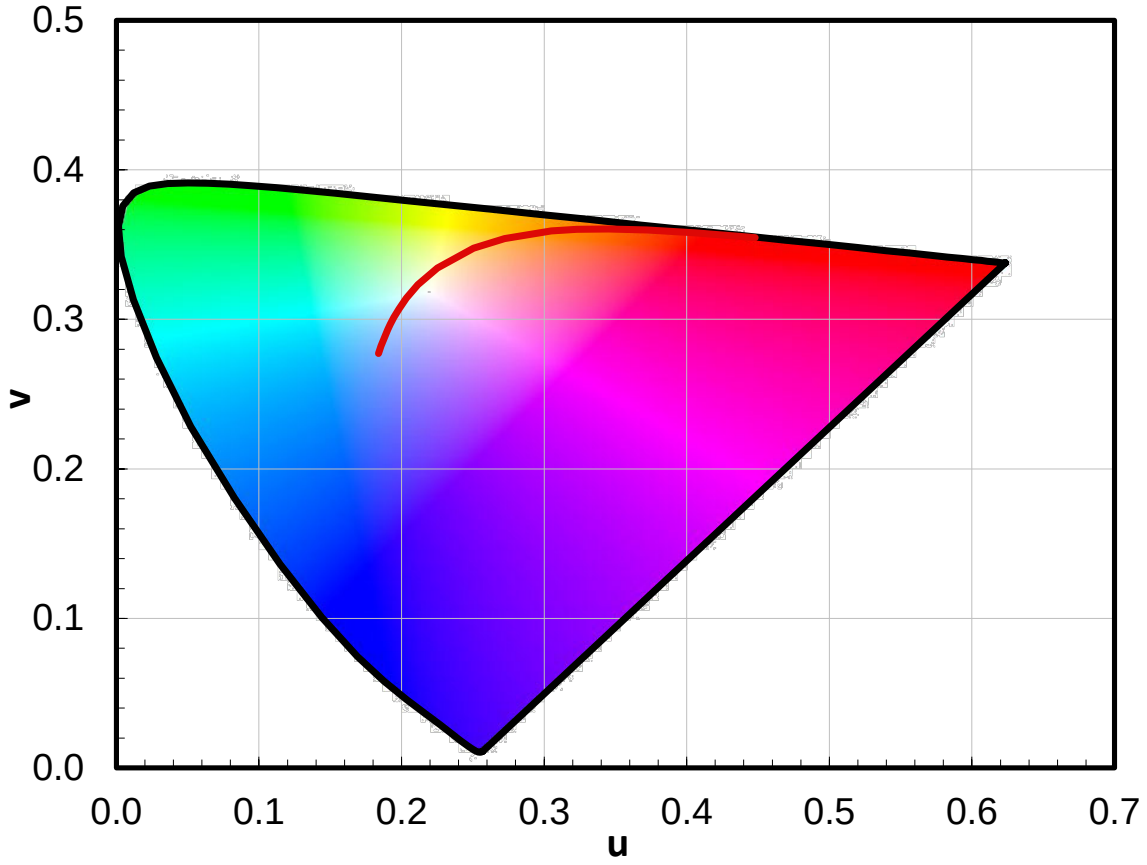
- Colors of the spectrum appear around upper edge (in nm)
- Bottom edge displays non-spectral colors; “purple line”
- Colored background is theoretical only; cannot be displayed accurately
- Black body locus (also called Planckian locus)
- **Use for light sources, not determining absolute appearance of objects!**

CIE 1931 (x, y) Chromaticity Diagram



- It's not perceptually uniform!!!

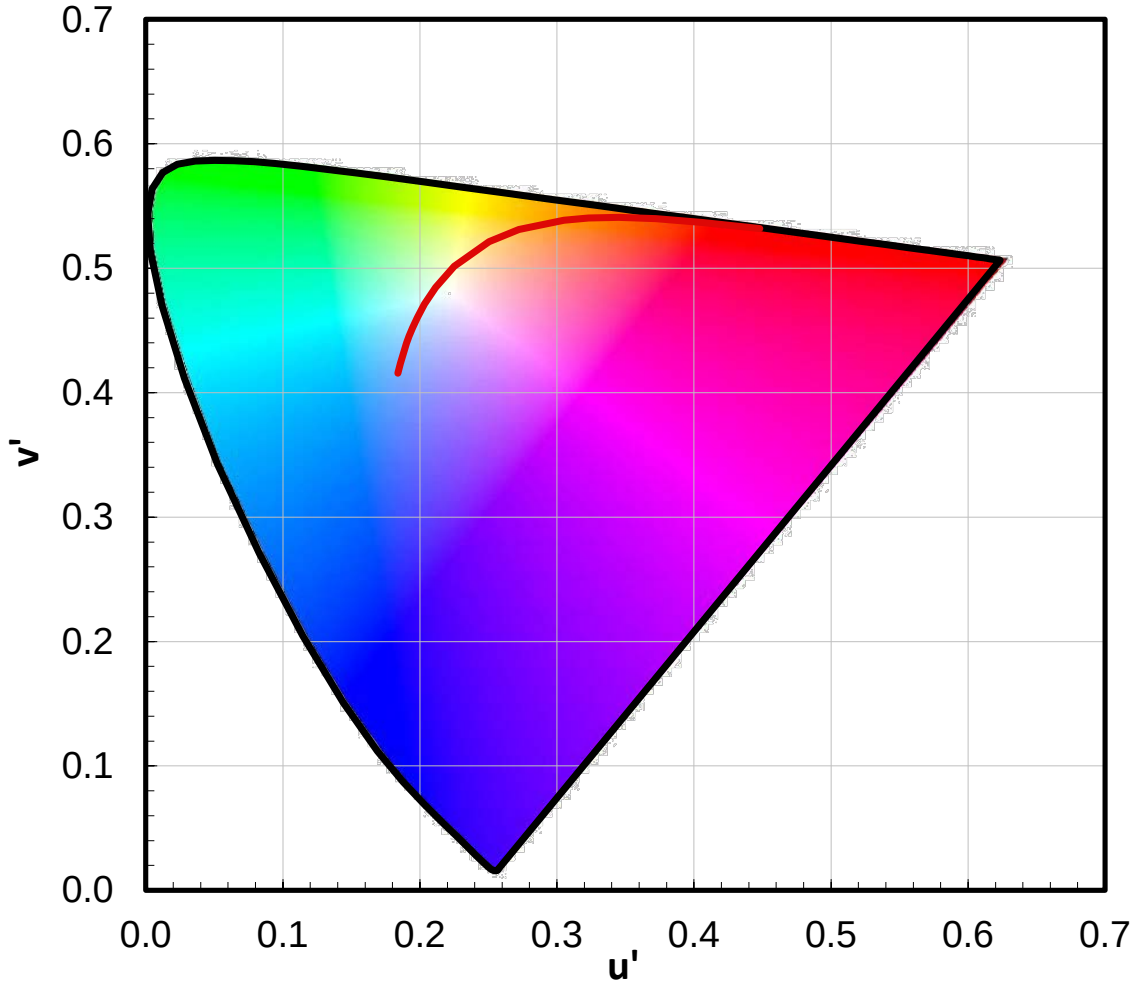
CIE 1960 (u, v) Chromaticity Diagram ("UCS")



$$u = 4x / (-2x + 12y + 3)$$
$$v = 6y / (-2x + 12y + 3)$$

- Simply linear transformation of CIE 1931 x-y
- u-v coordinates
- Intended to be more uniform (although not perfect)
- Used for calculating **CCT** and **D_{uv}**

CIE 1976 (u', v') Chromaticity Diagram

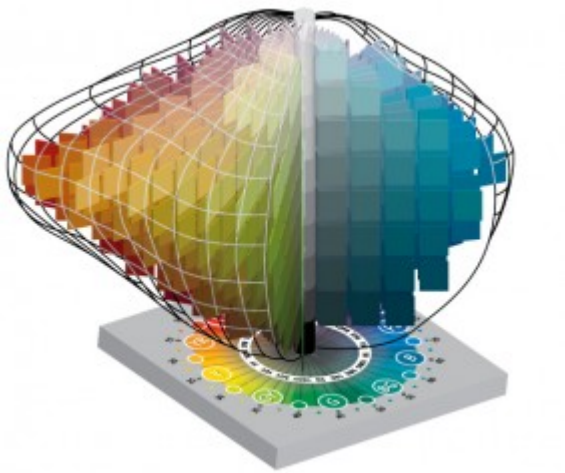


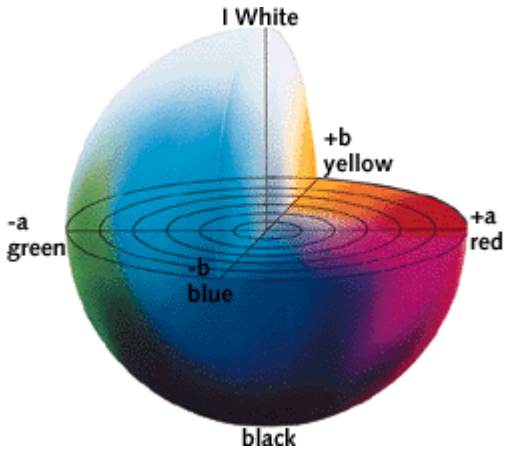
$u' = 4x / (-2x + 12y + 3)$
$v' = 9y / (-2x + 12y + 3)$

- Further transformation of CIE 1960 UCS (mulitple v by 1.5)
- u'-v' coordinates
- Is the most uniform available (still does not apply to objects)
- Used for calculating **Δu'v'**

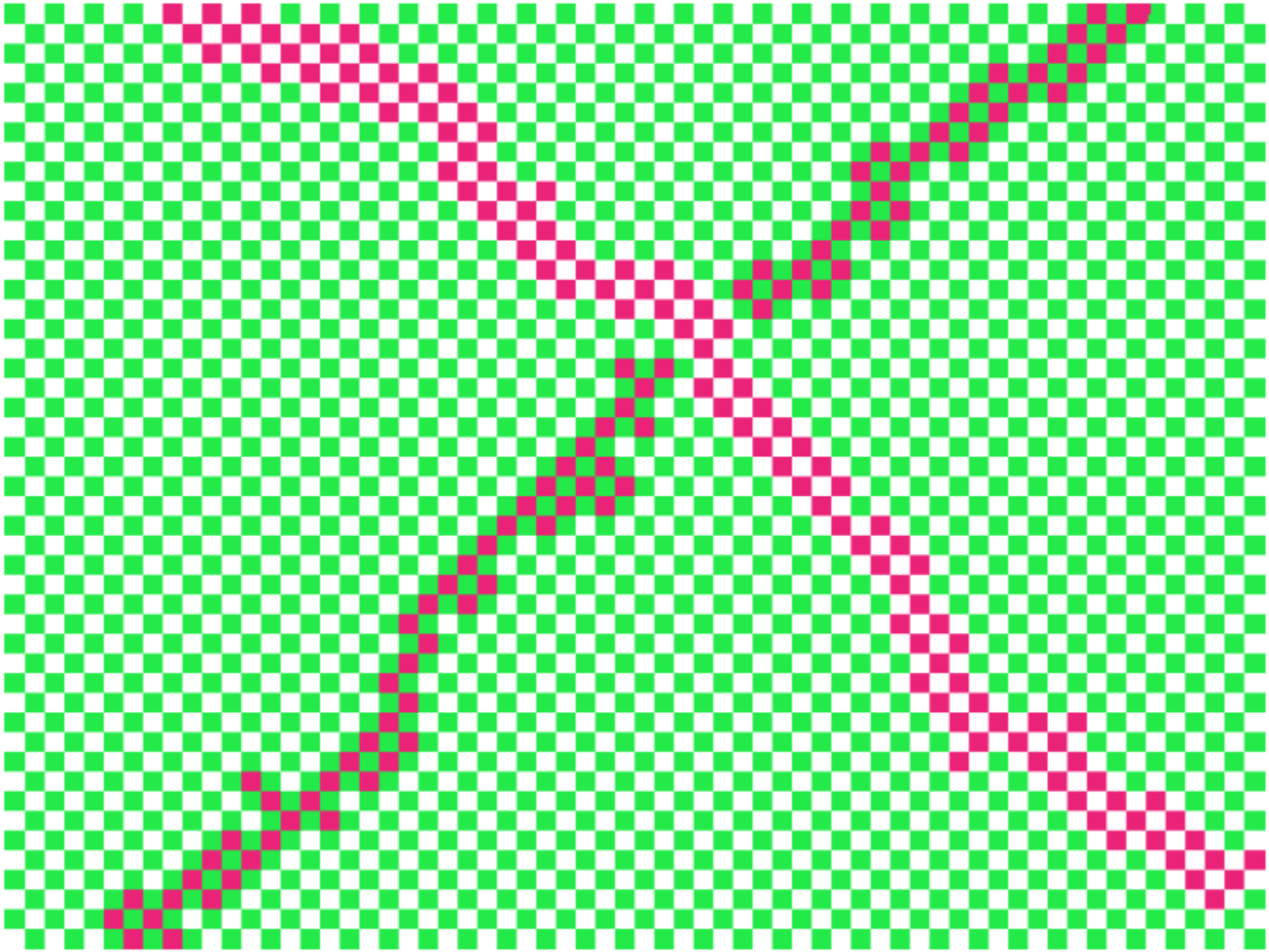
Object Color Appearance

- The dimension of *lightness* exists for objects
- Color solids (e.g., Munsell)
- Three-dimensional color spaces
  - CIE Lab
  - CIE Luv
- Color difference formula (ΔE^*_{ab}, ΔE^*_{oo})
- Chromatic adaptation
- Color Appearance Models (CAMs)
  - CIECAM02

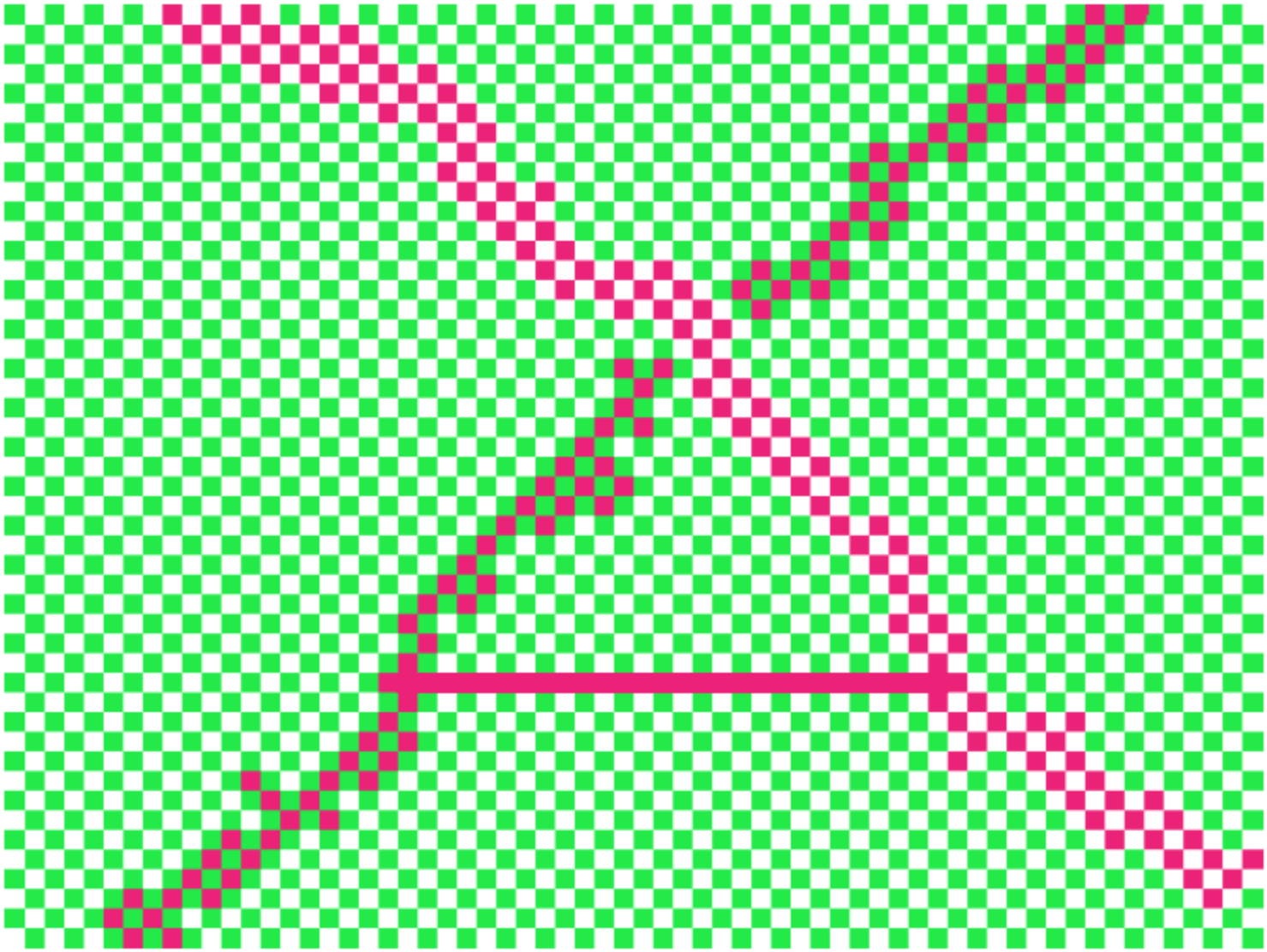




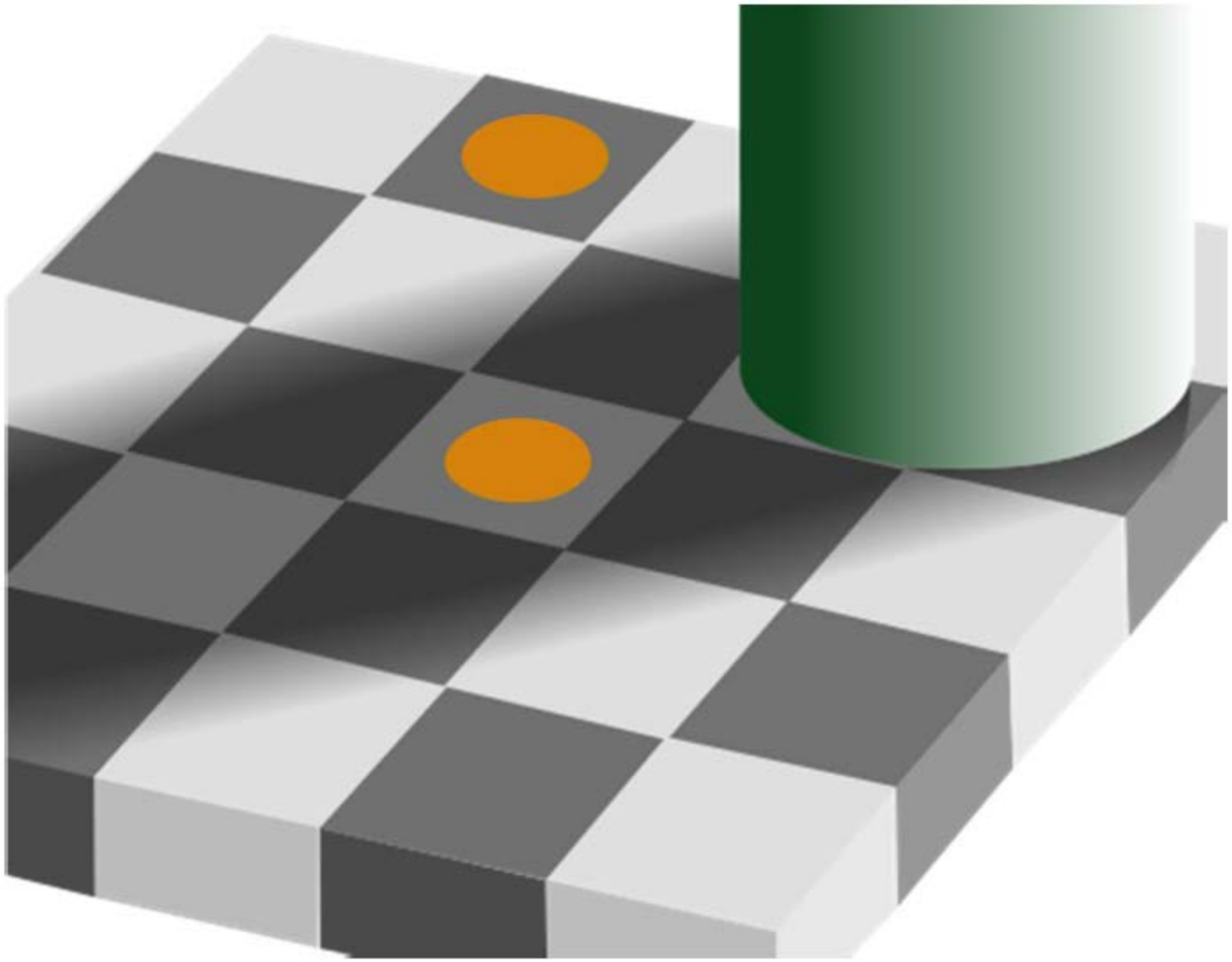
.....but.....



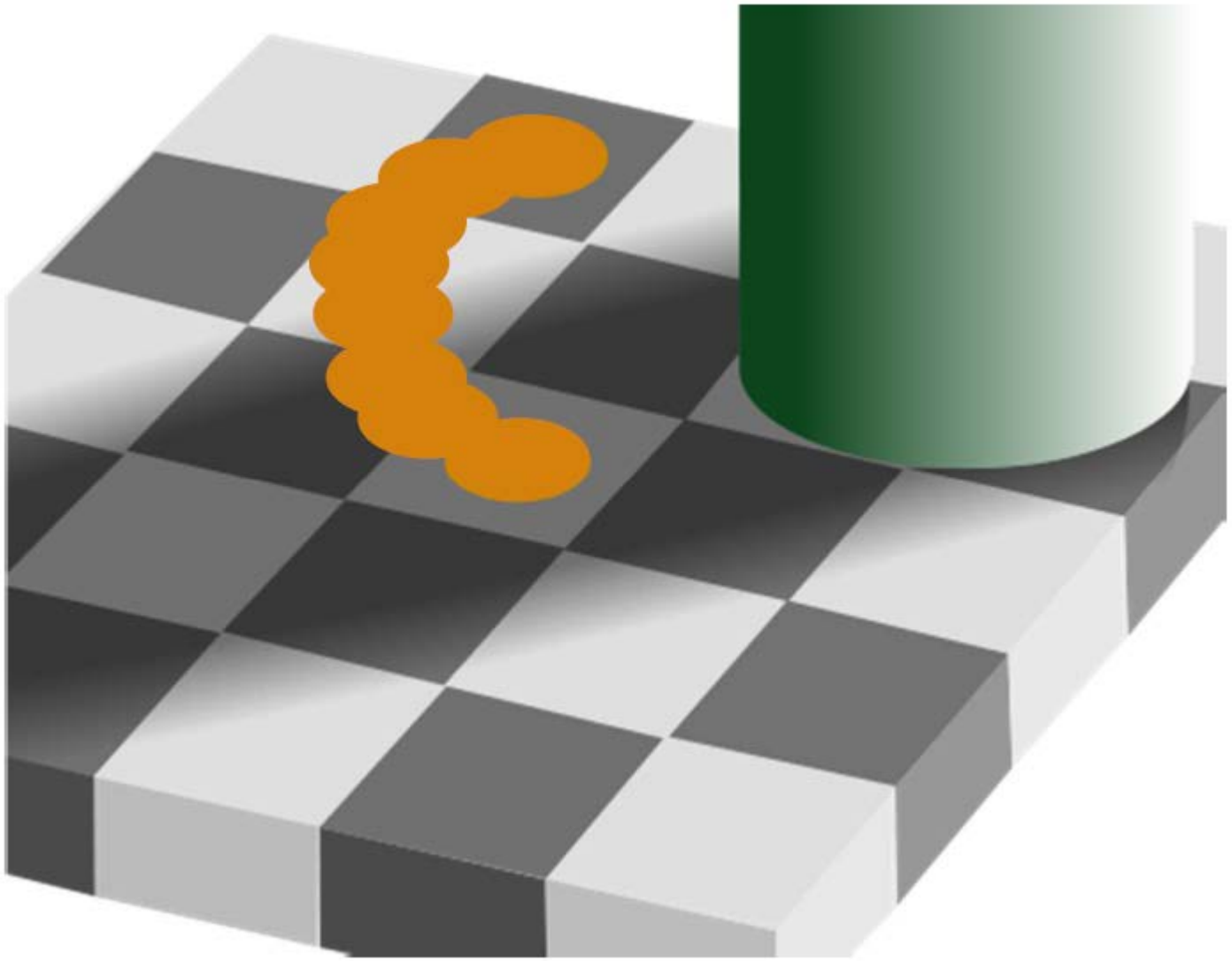
.....but.....



.....but.....



.....but.....



Bottom line: color science can't always describe human perception.

Color Appearance

Correlated Color Temperature (CCT)

D_{uv}

Δu’v’

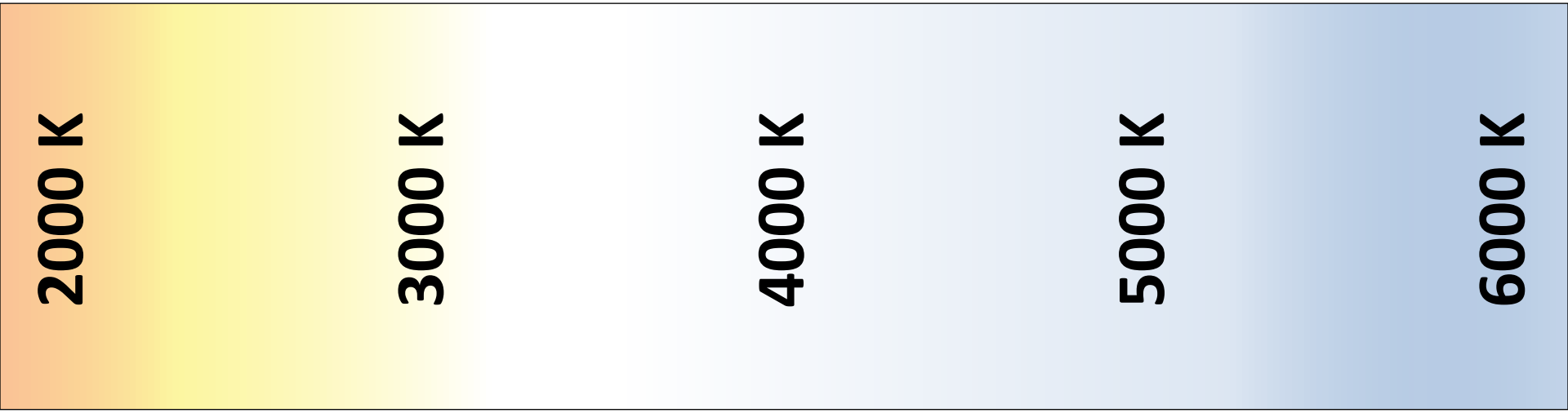
MacAdam Ellipses

Binning


Gates /


ICE HOCKEY
CHAMPIONS
2001
Bank young. Bank smart.

Correlated Color Temperature (CCT)

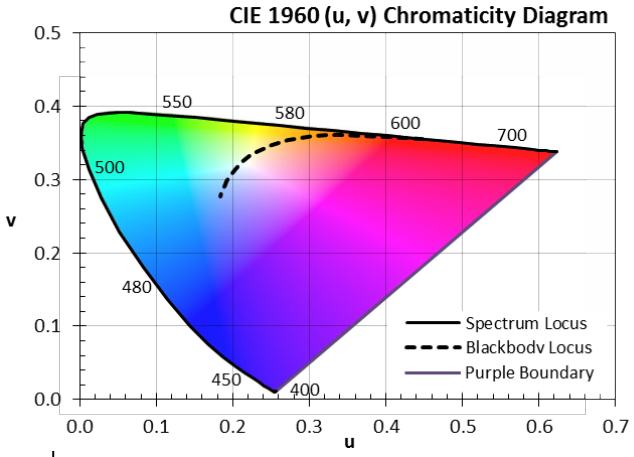


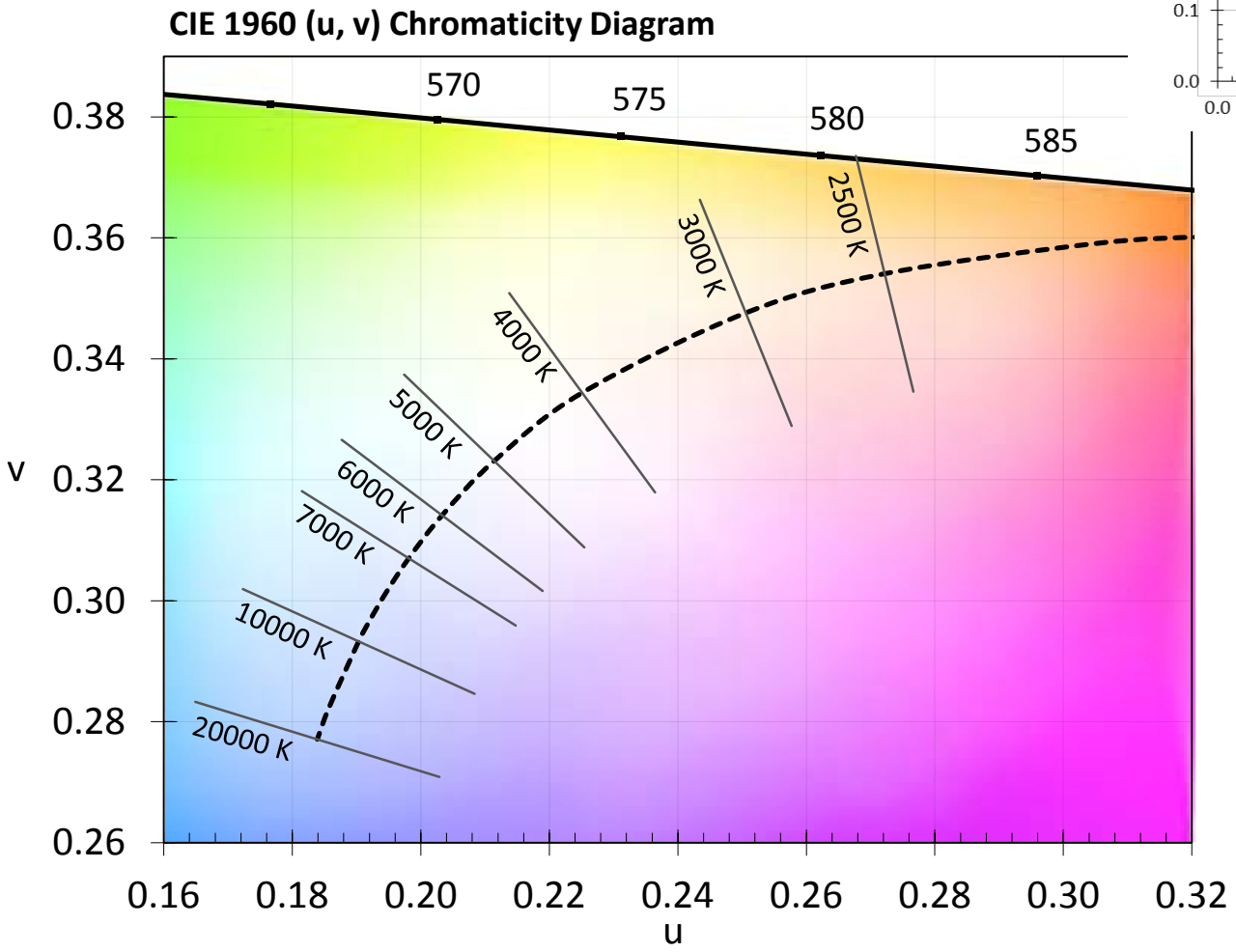
Approximate Illustration!

What about adaptation?

Our eye-brain system is very good at making these look the same!

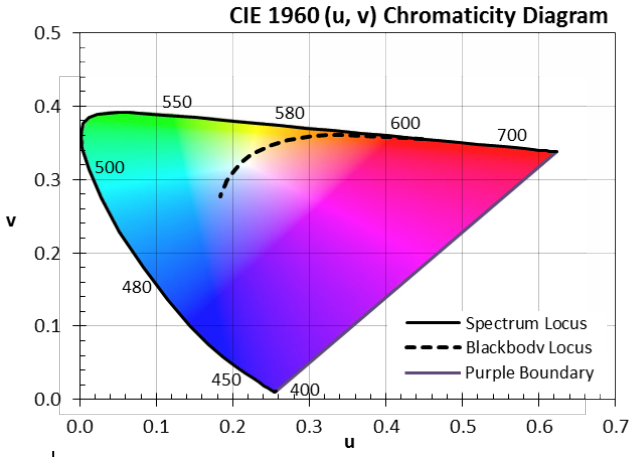
Correlated Color Temperature (CCT)

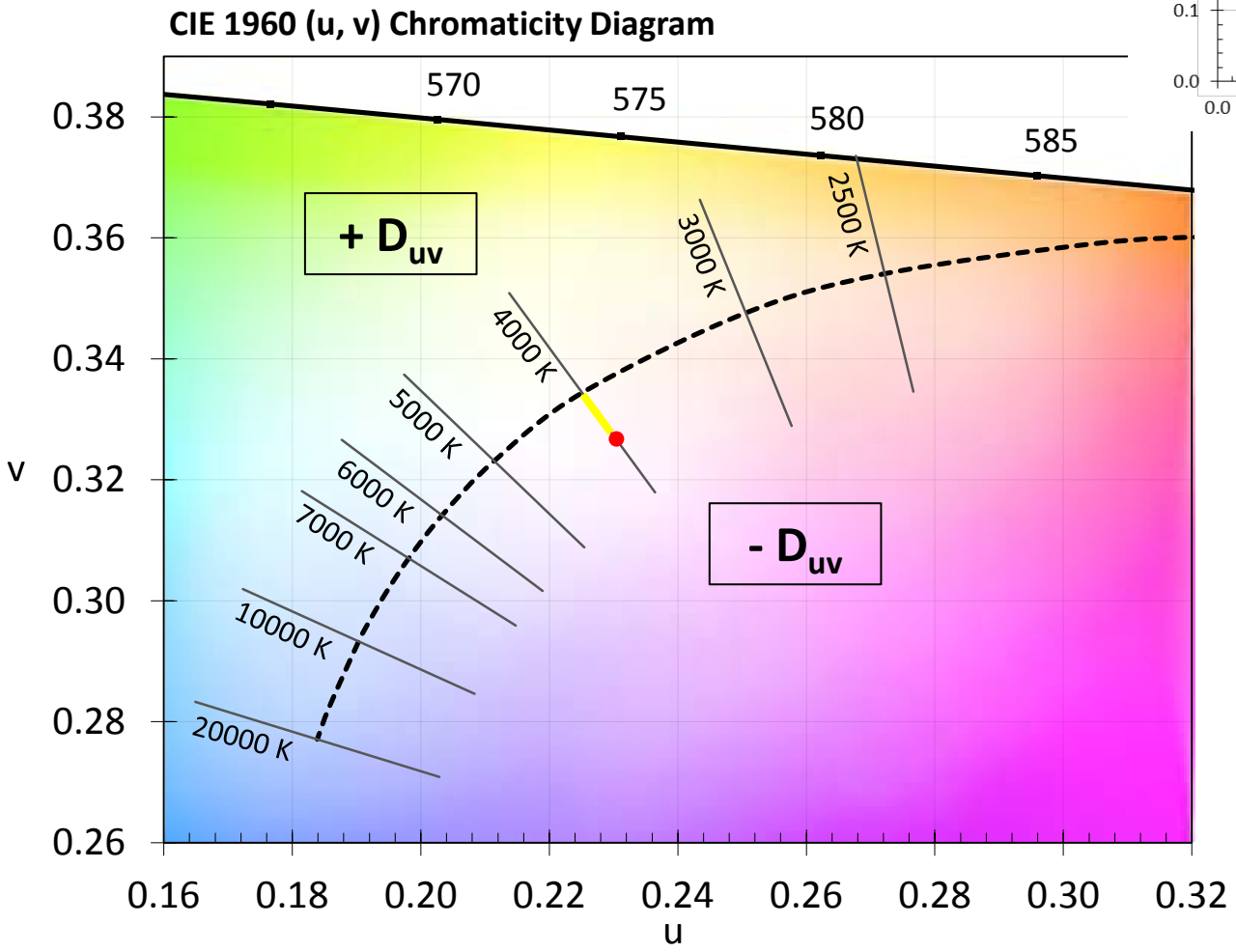




- Iso-CCT lines are perpendicular to Planckian locus in CIE 1960 UCS
- Two sources that appear very different can have the same CCT!

CCT + D_{uv}

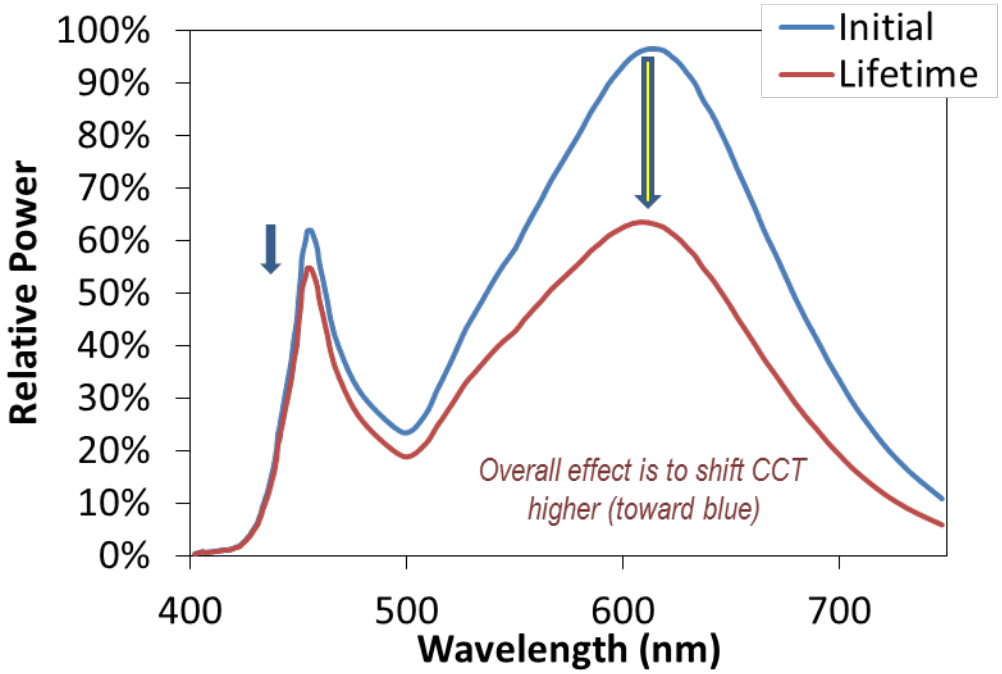




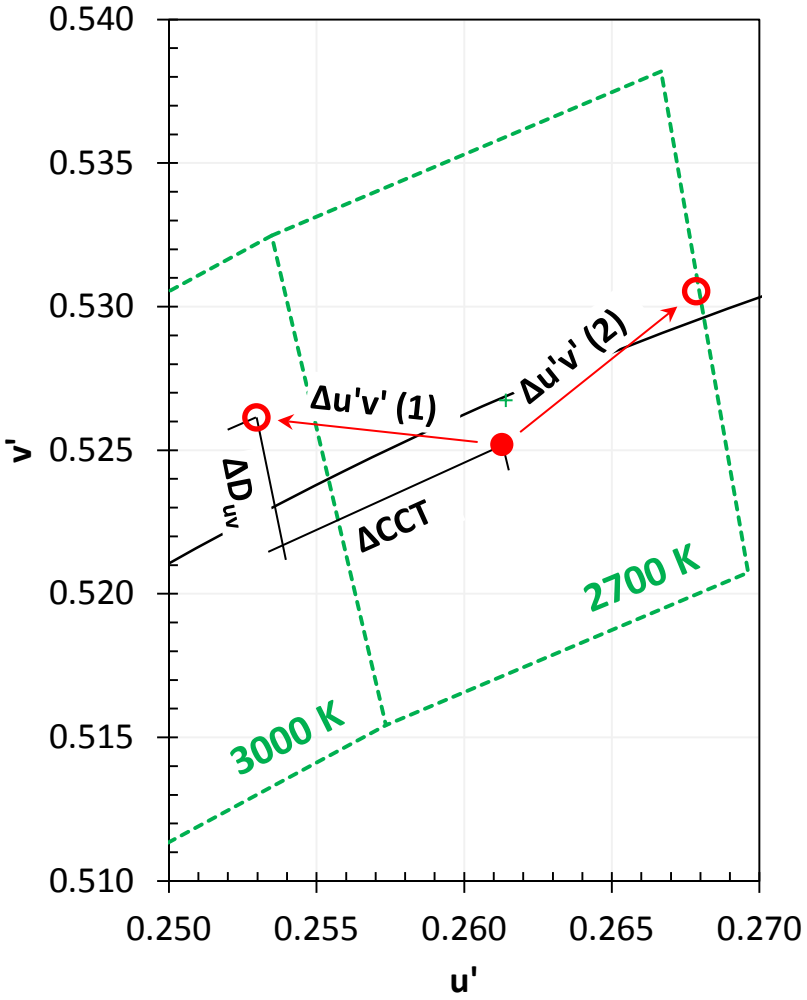
- D_{uv} adds a second dimension to better convey appearance
- Iso-CCT lines shown are ± 0.02 D_{uv}
- Typical limits for white light are -0.006 to 0.006 (but depends on CCT)

Color Maintenance

- Both LED output and phosphor performance degrade over time
- Phosphor performance can vary for different types, integration approaches, and/or manufacturers
- Faster phosphor degradation than blue die degradation can lead to color shift over time

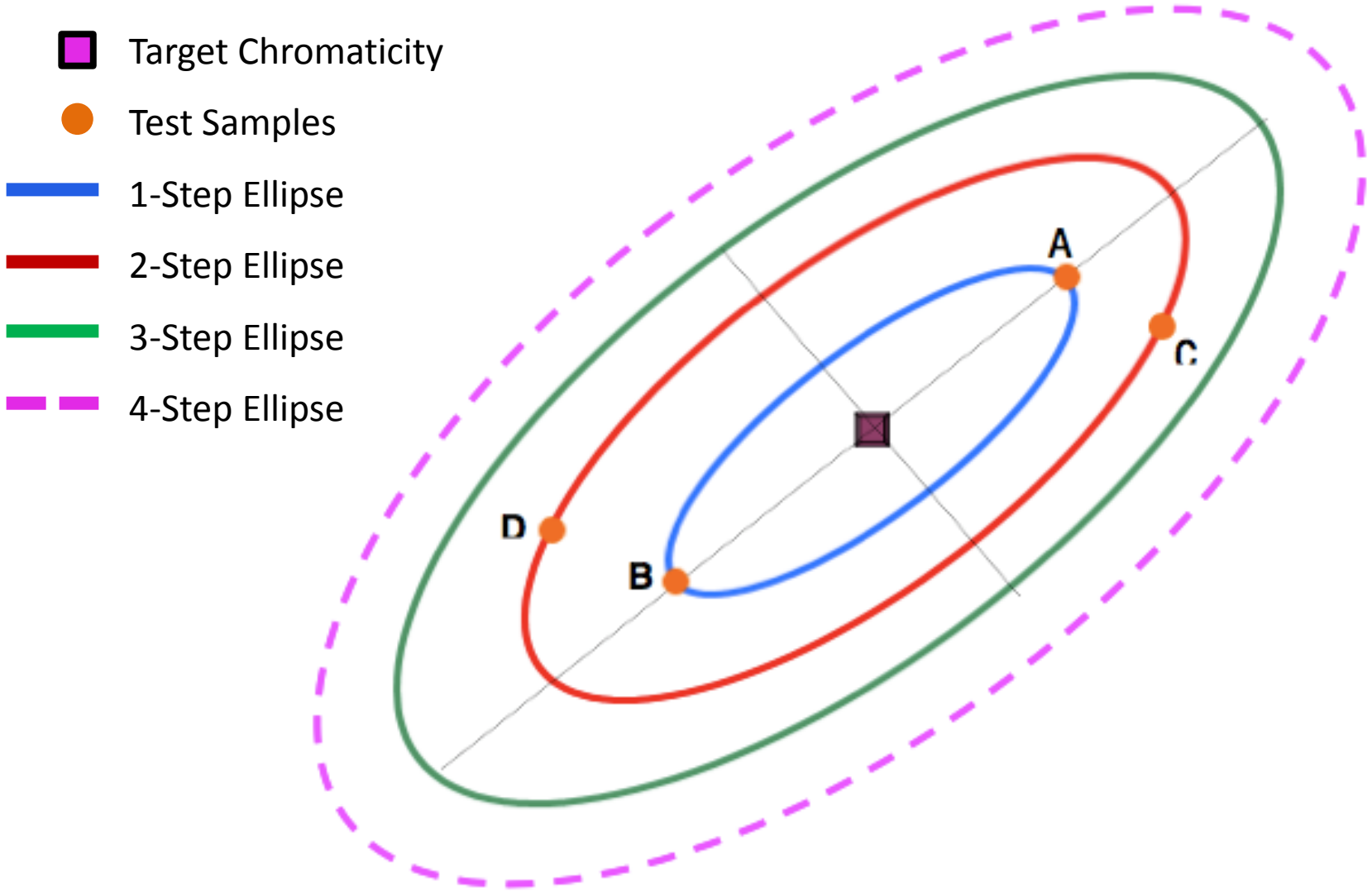


Describing Color Maintenance



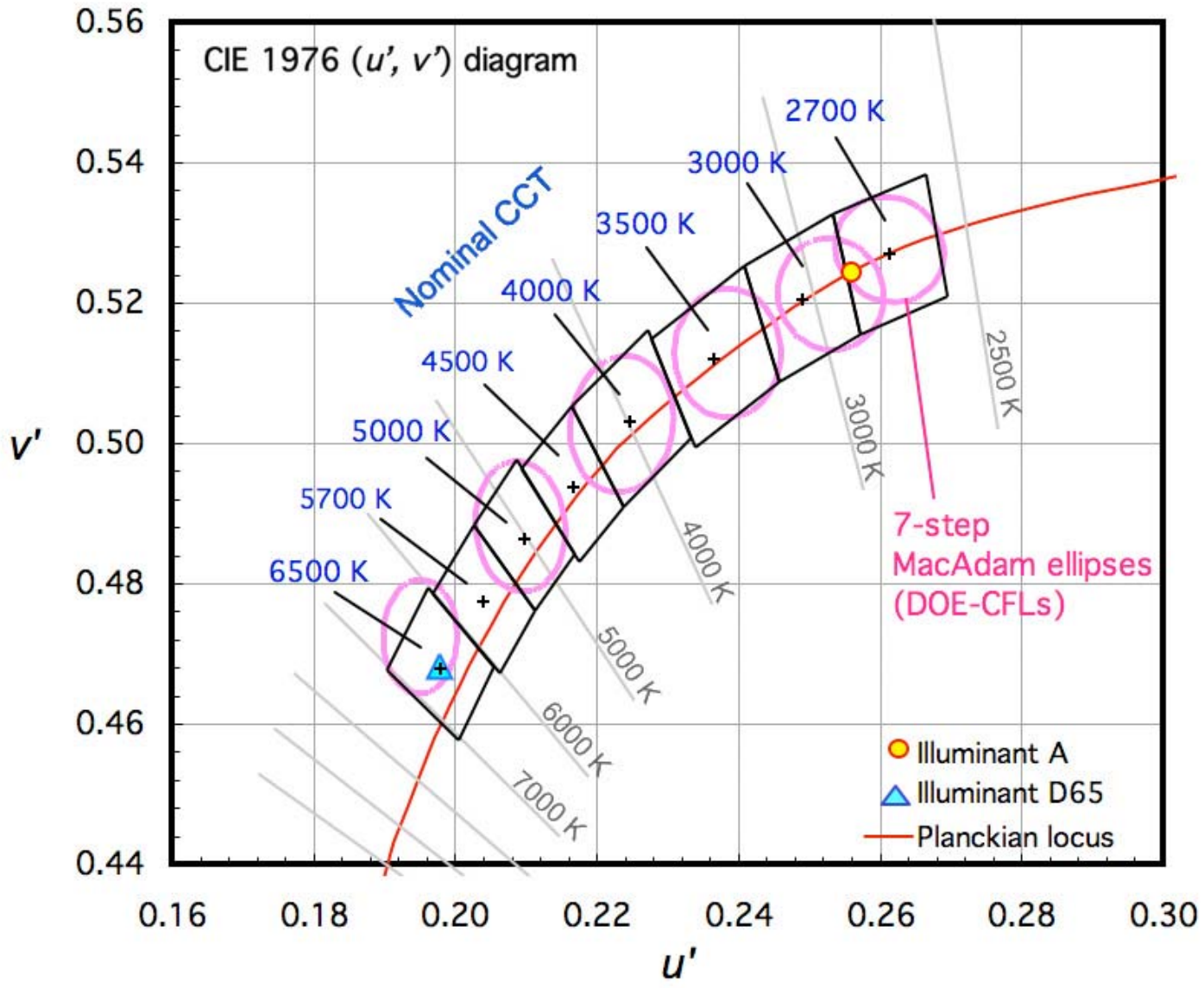
- Listing two CCTs from different points in time does not describe color difference
- Listing two D_{uv}s From different points in time does not describe color difference
- Use **Δu'v'**

MacAdam Ellipses



Note: A & B are 1 step from the Target, but 2 steps from each other!

Established Tolerances

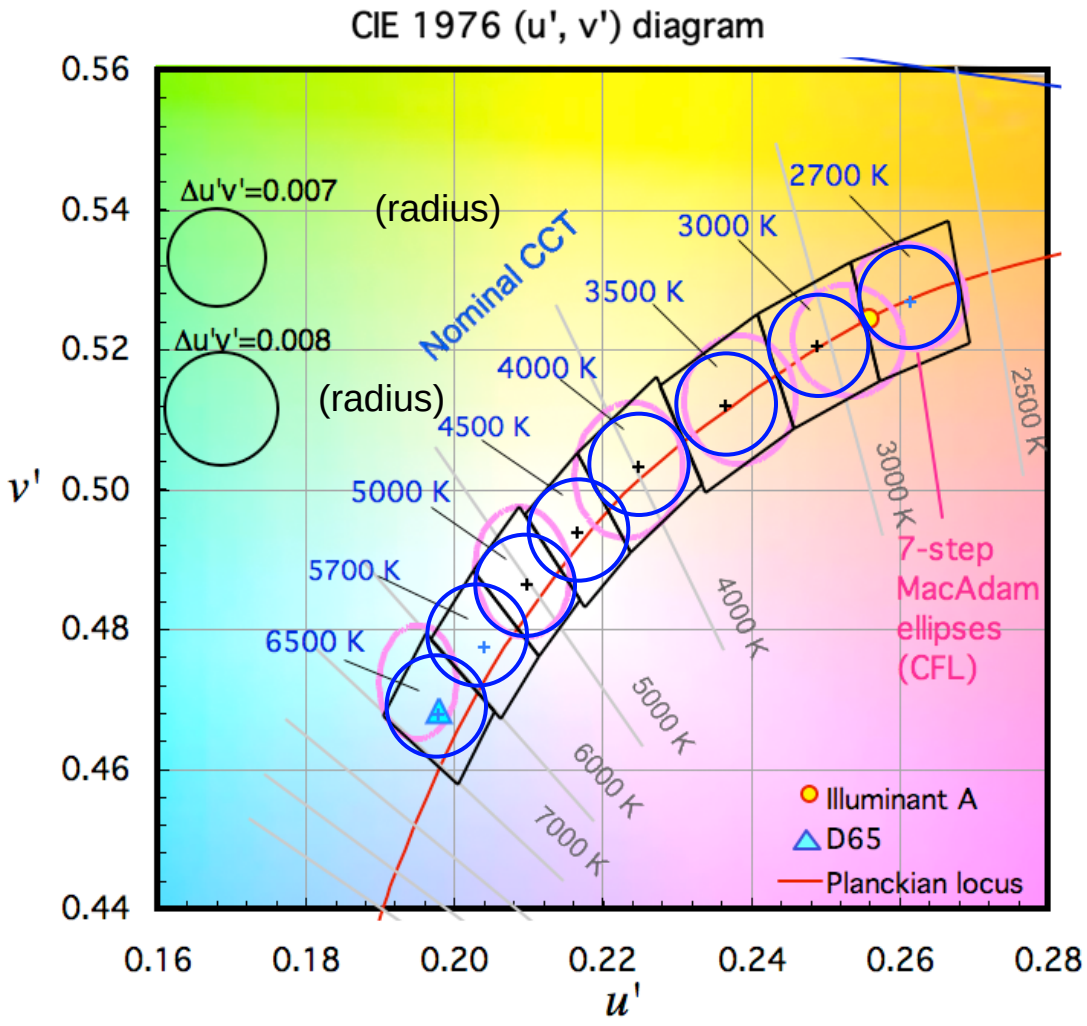


Linear Fluorescent:
4-step

CFL:
7-step

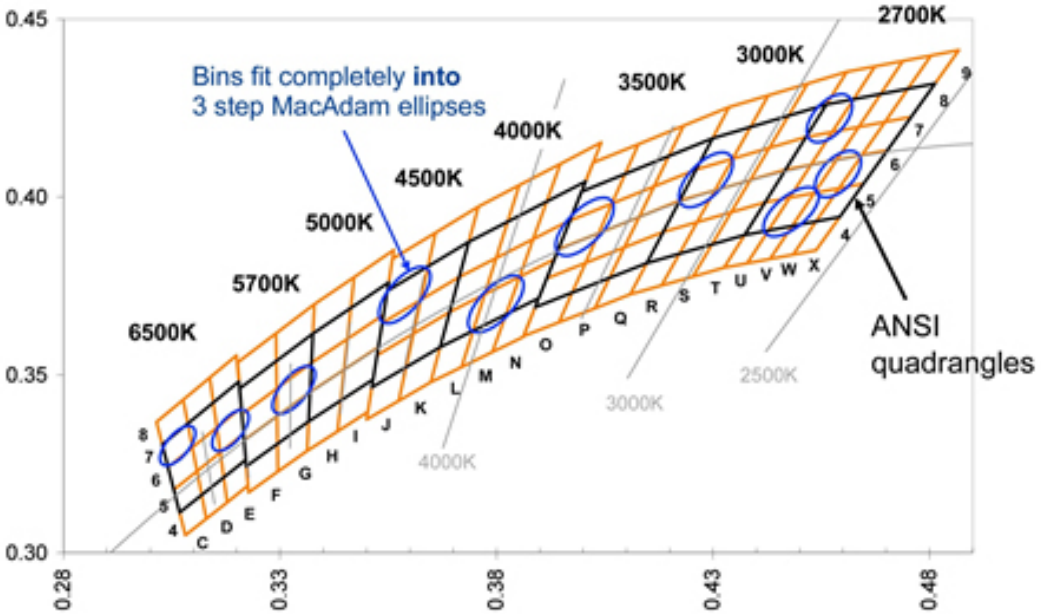
LED:
Quadrangle (Duv)

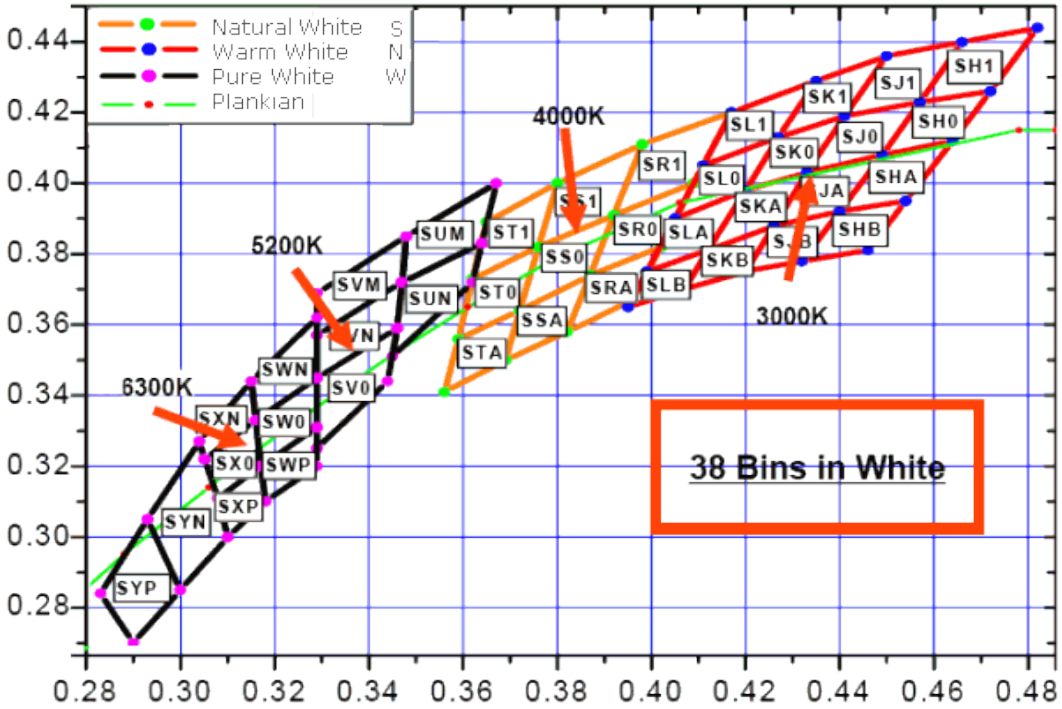
For Color Difference



- x-step MacAdam ellipses are approximately equal to circles with a radius 0.00x on (u'v') chromaticity diagram.
- Do not use x-step MacAdam ellipses to specify color differences.
- Use Δu'v'

Binning


Bins fit completely into
3 step MacAdam ellipses
2700K
3000K
3500K
4000K
4500K
5000K
5700K
6500K
ANSI
quadrangles
2500K
3000K
4000K
0.45
0.40
0.35
0.30
0.28
0.33
0.38
0.43
0.48


Natural White S
Warm White N
Pure White W
Plankian
4000K
5200K
6300K
3000K
38 Bins in White
0.44
0.42
0.40
0.38
0.36
0.34
0.32
0.30
0.28
0.28 0.30 0.32 0.34 0.36 0.38 0.40 0.42 0.44 0.46 0.48

Color Rendering

Color Rendering Index (CRI, Ra)

R9

Color Quality Scale (CQS)

Others

Color Appearance & Preference

Retail (produce)

Homes

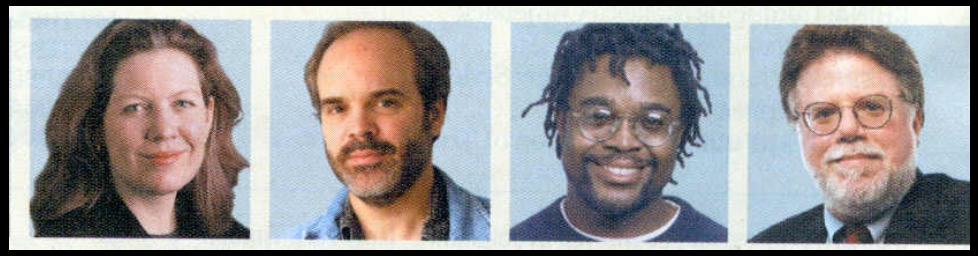
Retail Clothing / Furnishings

Color Appearance & Preference

Hospitality (Hotel/Spa/Restaurant)

Face-to-face Communication

Color Appearance & Preference



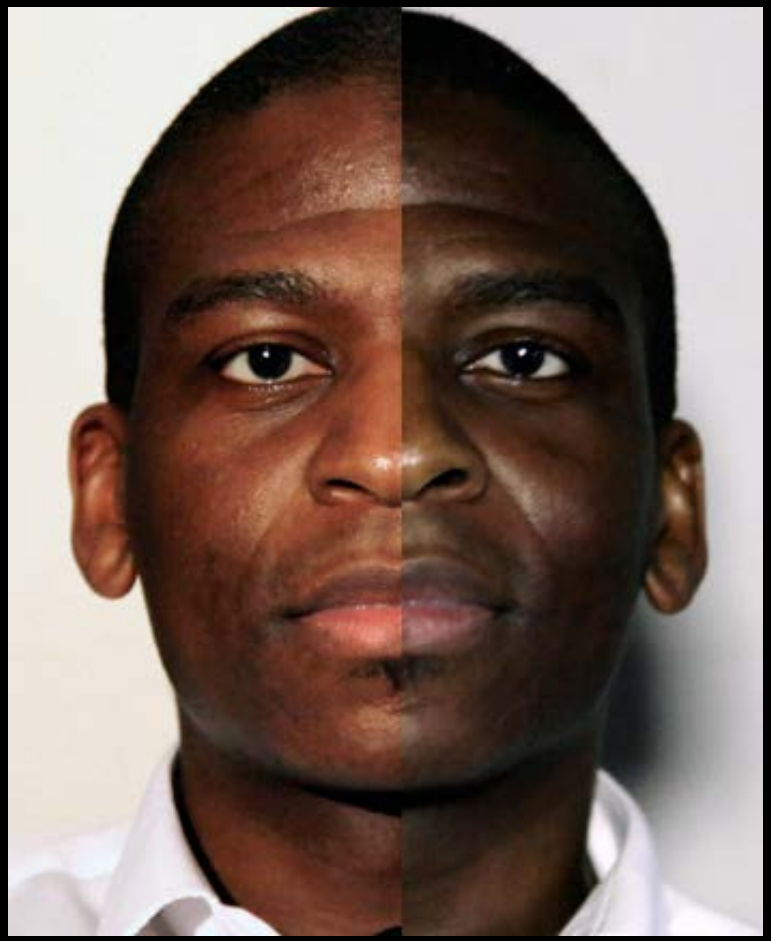
Anywhere faces are important

Anywhere food is served

Color Appearance & Preference

An illustration of the differences on camera between daylight and basic white LED lighting of the same color temperature. Note the first two patches on the test chart represent “skin” tones.

Color Appearance & Preference



The picture illustrates the impact on skin tones while using LED lighting. Skin tones should appear natural, otherwise the subject could look ill.

Color Fidelity

Food
Inspection

Healthcare
(jaundice, redness, cyanosis)

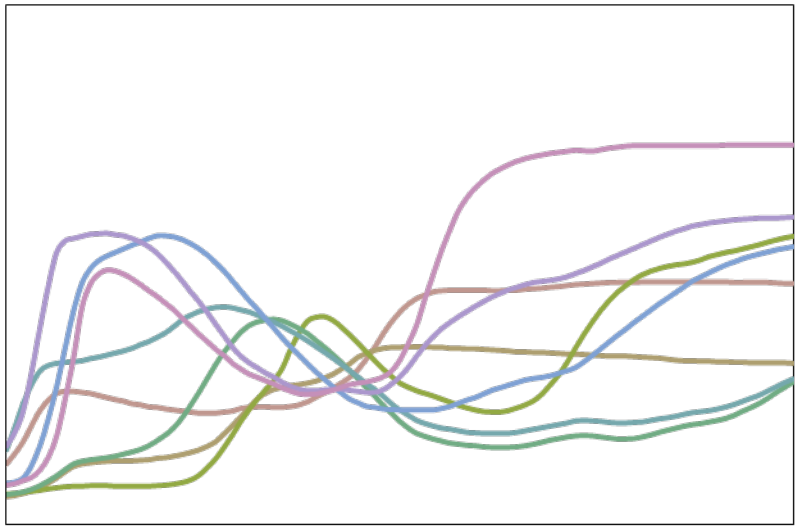
Industrial Color Matching,
Interior Design Selections

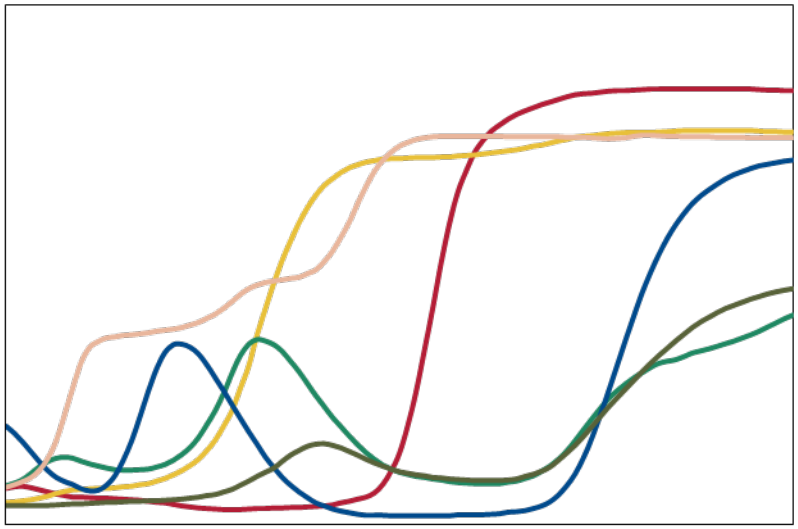
Color Rendering Index (CRI) Ra

The basics:

- Compares chromaticity of eight (pastel) test color samples under test illuminant to reference illuminant
- It's 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
- Ra is part of a larger system that includes 14 (now 15) total samples
- Applicable to sources near blackbody locus
- Does not predict appearance of specific objects

CRI: The methods behind the metric





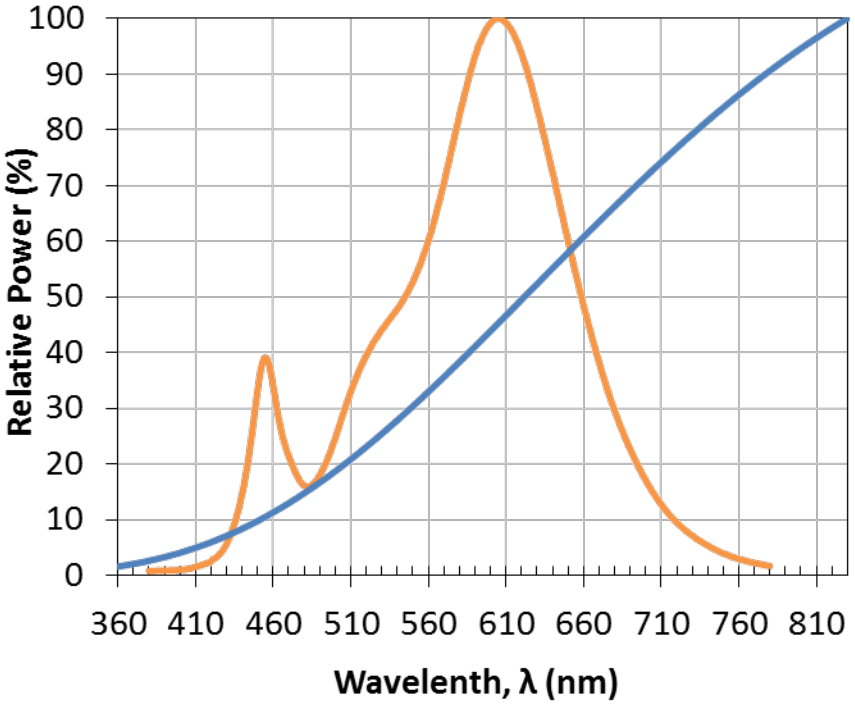
Approximation of Color Samples for CRI R_a (3000 K Blackbody Radiation)

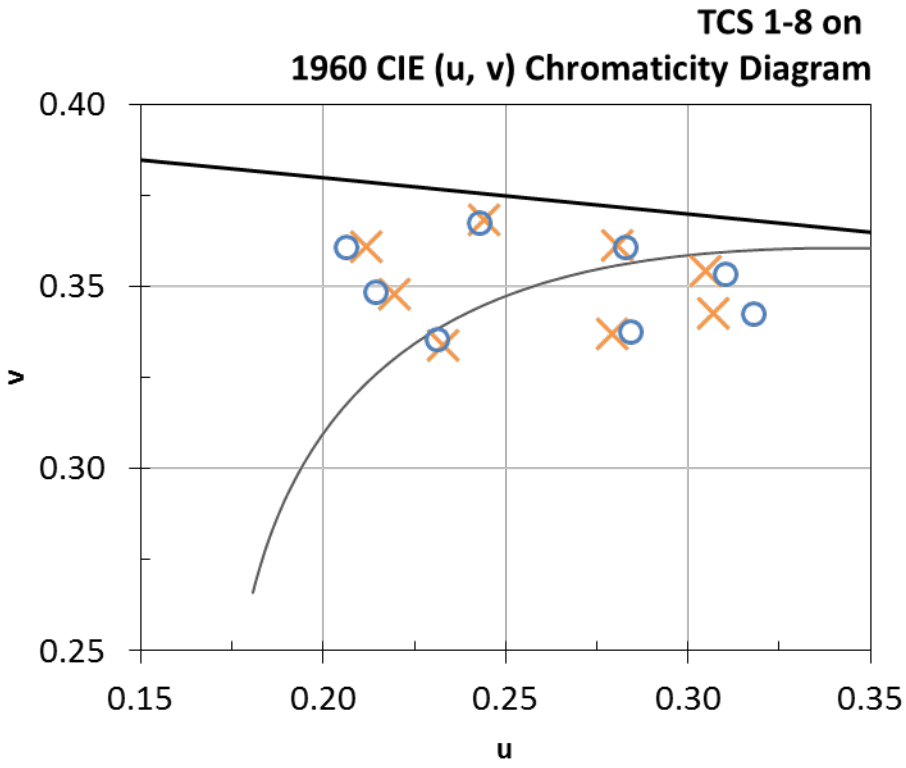
TCS 01 TCS 02 TCS 03 TCS 04 TCS 05 TCS 06 TCS 07 TCS 08

Color Samples for R_9–R_{14}

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

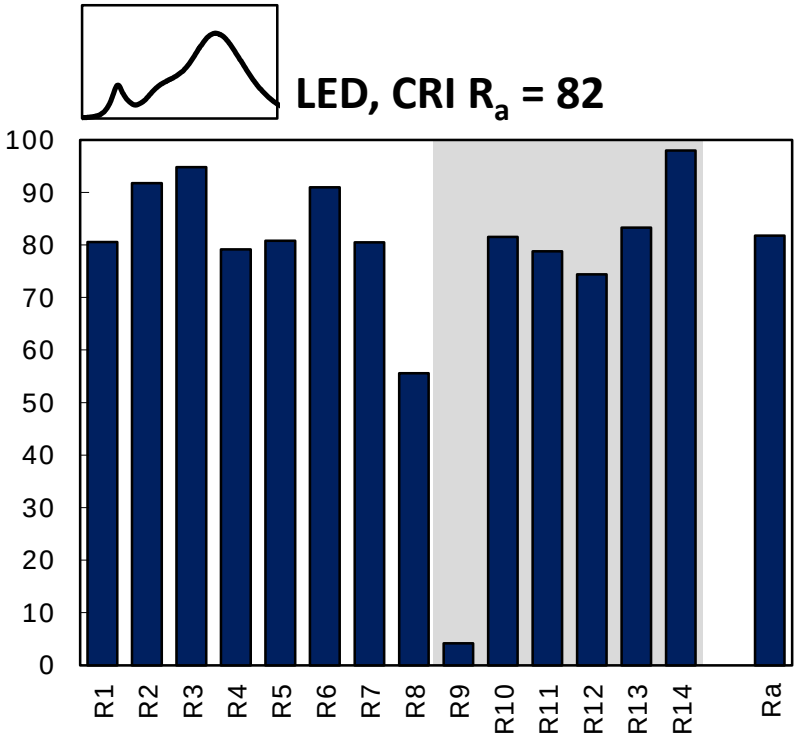
CRI: The methods behind the metric

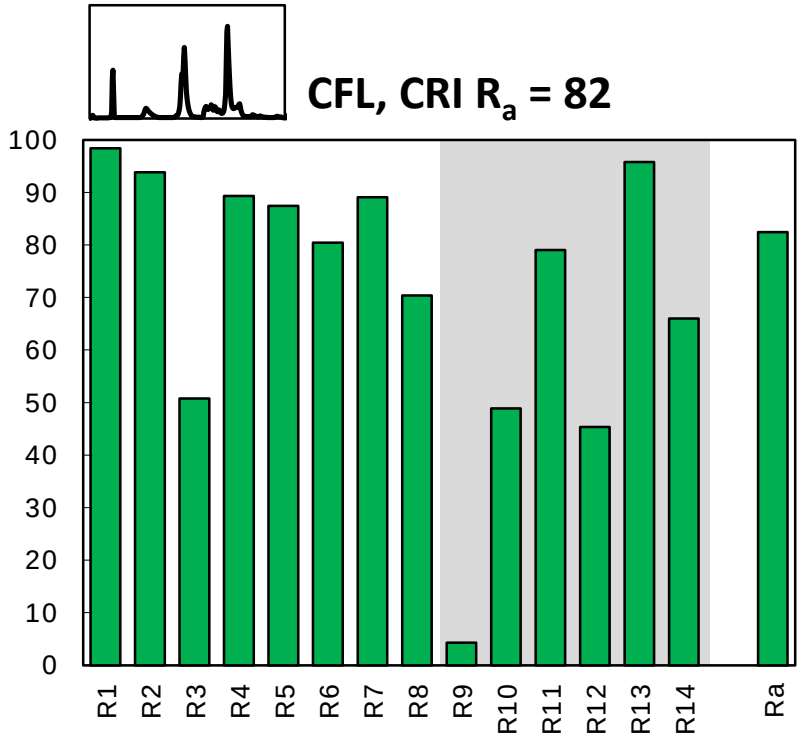




Limitations of CRI

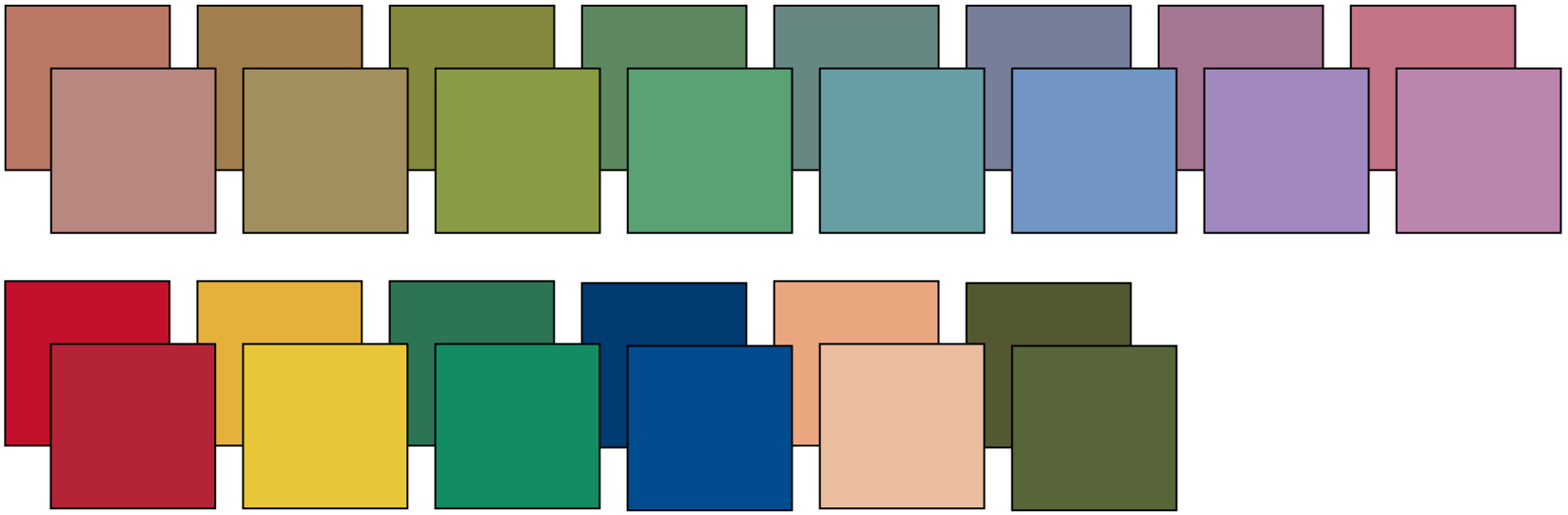
- Averaging, references and other methodological issues
- Does not convey exact color appearance
  - Very saturated could be the same as very unsaturated
- Does not work well for very discrete SPDs (i.e., RGB LED)





Different References

2700 K (back) versus 6500 K (front)



Objects will looks different under sources with same CRI at different CCTs

(although chromatic adaptation helps)

Special Color Rendering Index R_9

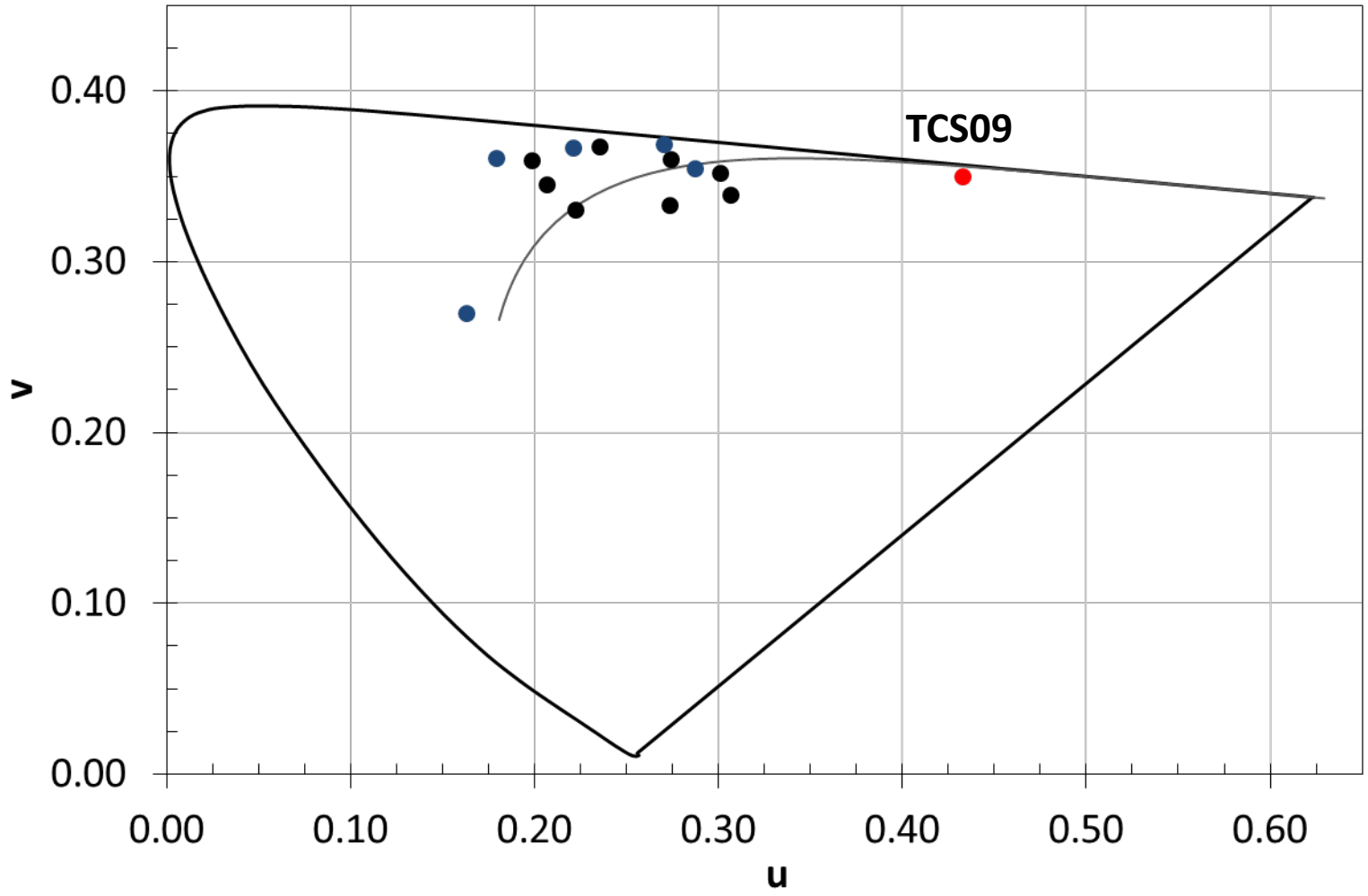
The basics:

- Part of the same system as CRI Ra
  - Same calculation method
- Saturated red
- Red is particularly important for human skin complexion
- Often considered a valuable supplement to CRI Ra

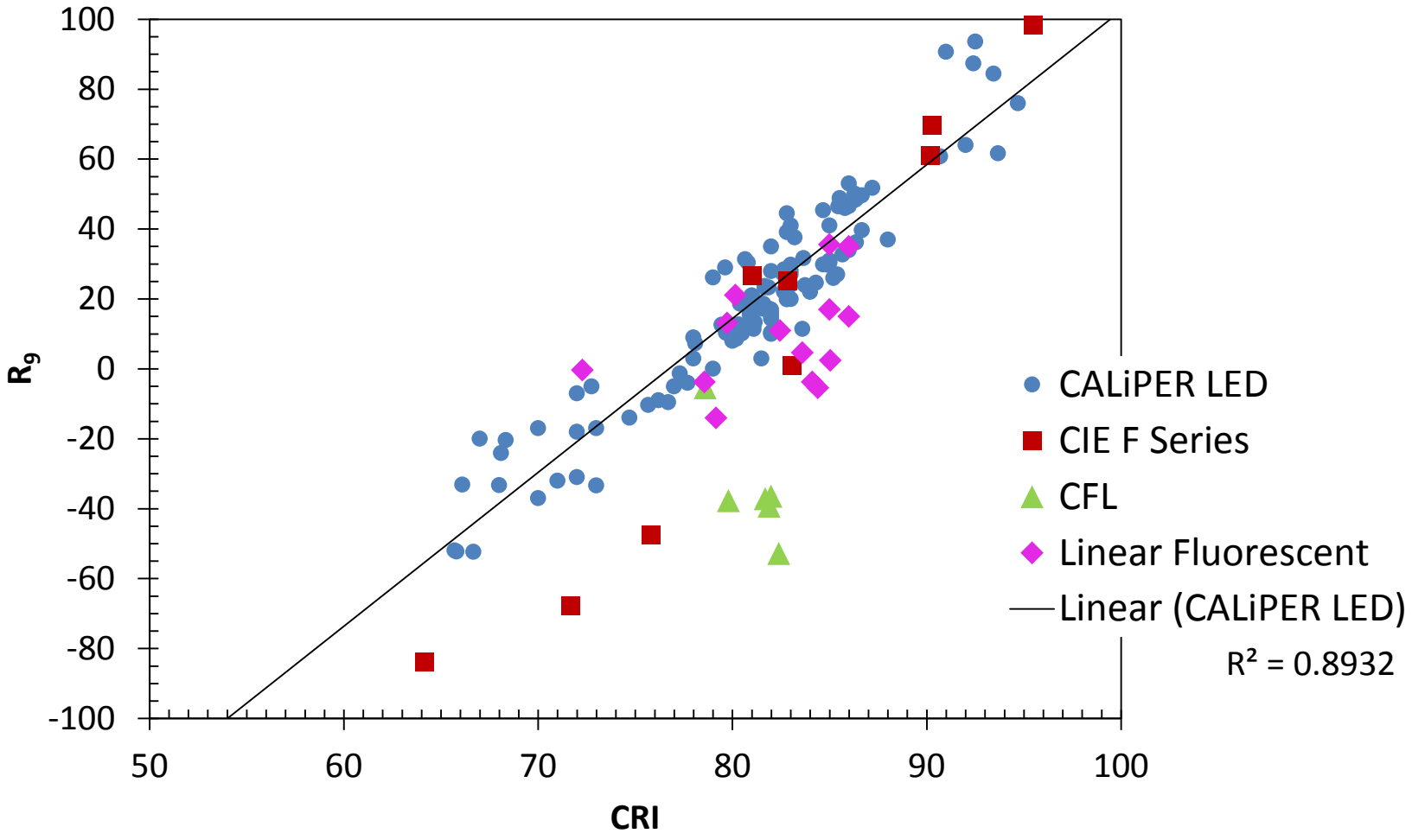
Because color space is skewed at red…
R_9=0+ is Good; R_9=50+ is Very Good; R_9=75+ is Excellent

[Equivalent R_9 CRI = 100 – (100-R_9)/4]

Special Color Rendering Index R_9



CRI versus R_9



Other Color Rendering Metrics

Recent

- CQS – Color Quality Scale
- n-CRI
- Philips CRI
- MCRI (Memory Color)
- Colour Category Index
- Darmstadt RCRI
- Feeling of Contrast
- CRI-CAM02UCS
- GAI – Gamut Area Index

…and many others!

Older

- CPI – Color Preference Index
- CDI – Color Discrimination Index
- CRC – Color Rendering Capacity
- CSA – Cone Surface Area
- Pointer Index
- Flattery Index

…and many others!

The Future of Color Rendering Metrics

- **Is there a perfect metric for all situations?**
- **Who needs what information?**
- **How similar should new metrics be to existing metrics?**

Halogen
99 CRI , 2917 K, D_{uv} 0.000

Metrics aren't perfect!

Compact Fluorescent
82 CRI, 2731 K, D_{uv} 0.003

LED
84 CRI, 2881K , D_{uv} 0.000

Conclusions + Notes

- It is important to understand the limitations/intended use of the various color metrics
- 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*.

- Energy efficiency standards should include minimum targets for color temperature, color rendering, and color maintenance
- Standardized photometry should include SPD, CRI, CCT and Duv
  - With an SPD, it should be possible to calculate a large range of metrics

Thanks!

Naomi Miller
Pacific Northwest National Laboratories
Portland OR
Naomi . Miller @ PNNL . gov

Michael Royer
Pacific Northwest National Laboratories
Portland OR
Michael . Royer @ PNNL . gov