Color in Displays

Michael J. Murdoch
Munsell Color Science Laboratory
Rochester Institute of Technology

Introduction: Mike Murdoch

- Assistant Professor in Color Science @ RIT since 2015
- Research Topics: Visual adaptation, color and material appearance, AR display applications, dynamic lighting
- Philips Research (Eindhoven, NL) 2008-2015
- Kodak Research (Rochester, NY) 1997-2008
- Chemical Engineering / Computer Science / Human-Technology Interaction (PhD: Human-Centered Display Design)
- Photography, snowboarding, xc skiing, kayaking, maker stuff

Munsell Color Science Laboratory at RIT: mcsl.rit.edu

- Color Science MS & PhD program
- Colorimetry, vision, color physics, psychophysics,…
- Displays, printing, 3D printing, color appearance, graphics, VR/AR, LED lighting

Basic Additive Display Concepts

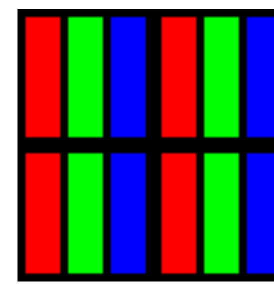
Additive RGB

- Primaries: Red , Green , and Blue
- A display is an additive system, meaning colors may be synthesized using linear combinations of the primaries.
- Example: 0.8 * =

  0.6 * =

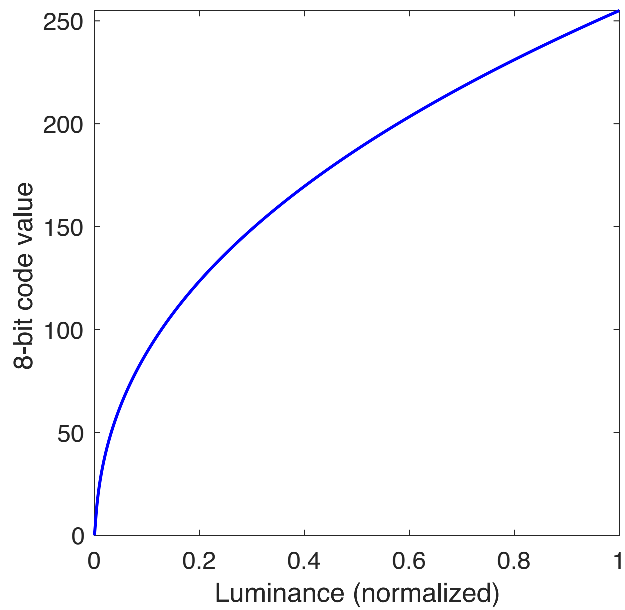
  0.2 * =

  \+



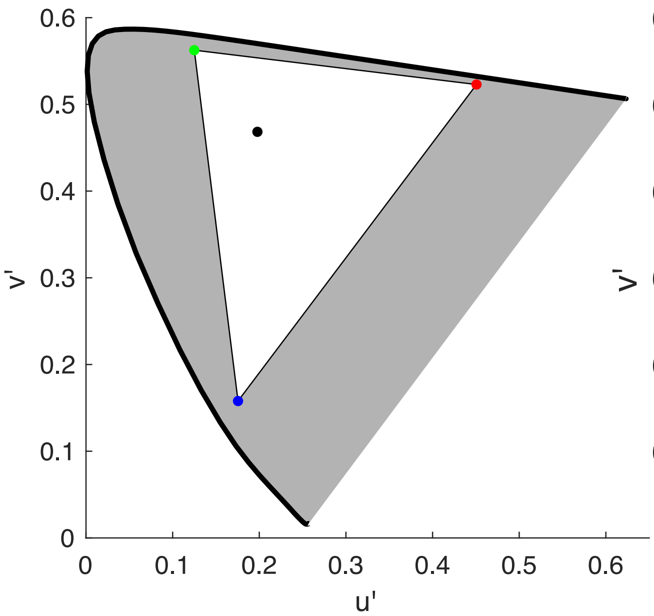
Additive *Nonlinear* RGB

- Thanks to EOTF: RGB Code Values are nonlinear
- Using an sRGB monitor, linear intensity values (0.8, 0.6, 0.2) correspond to 8-bit nonlinear code values (231, 203, 124).

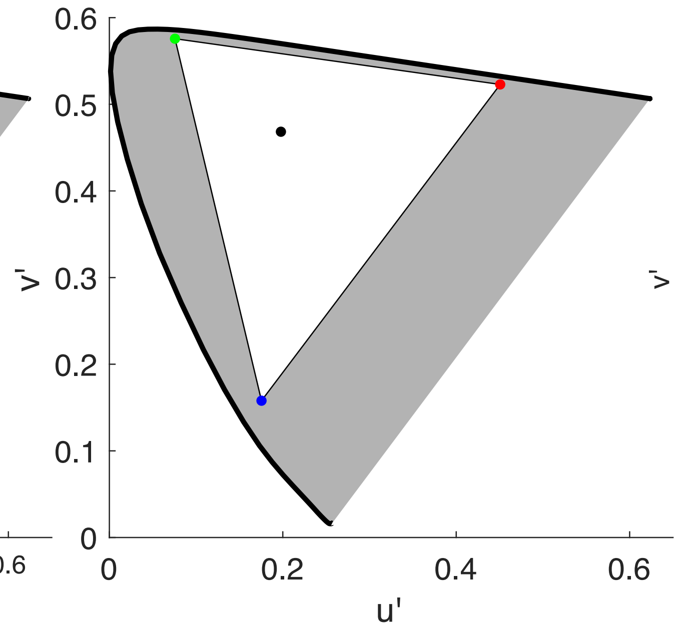


But *Which* RGB?

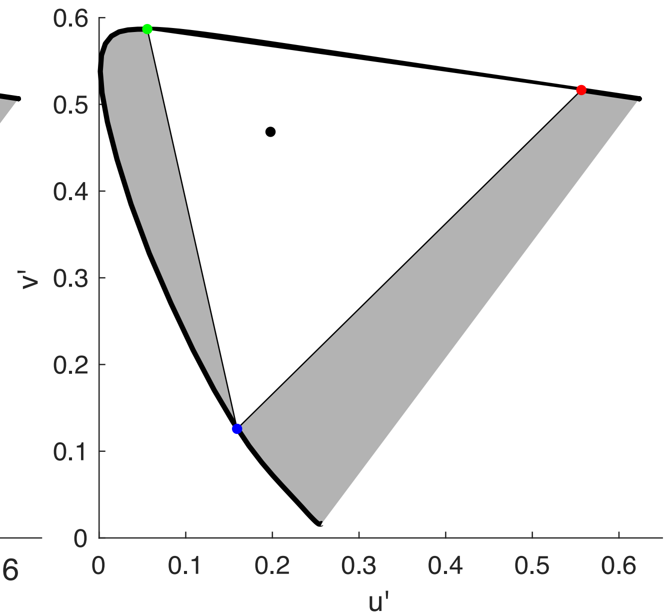
Rec 709 / sRGB



Adobe RGB



Rec 2020 & 2100



http://www.itu.int/rec/R-REC-BT.709
https://www.adobe.com/digitalimag/pdfs/AdobeRGB1998.pdf

https://www.itu.int/rec/R-REC-BT.2020
https://www.itu.int/rec/R-REC-BT.2100

Linear Combinations: Additivity

$$S(\lambda) = \sum_{i=1}^{n} p_i \, S(\lambda)_i$$

$$\begin{bmatrix} S(\lambda_1) \\ \vdots \\ S(\lambda_m) \end{bmatrix} = \begin{bmatrix} S(\lambda_1)_1 & \cdots & S(\lambda_1)_n \\ \vdots & \ddots & \vdots \\ S(\lambda_m)_1 & \cdots & S(\lambda_m)_n \end{bmatrix} \begin{bmatrix} p_1 \\ \vdots \\ p_n \end{bmatrix}$$

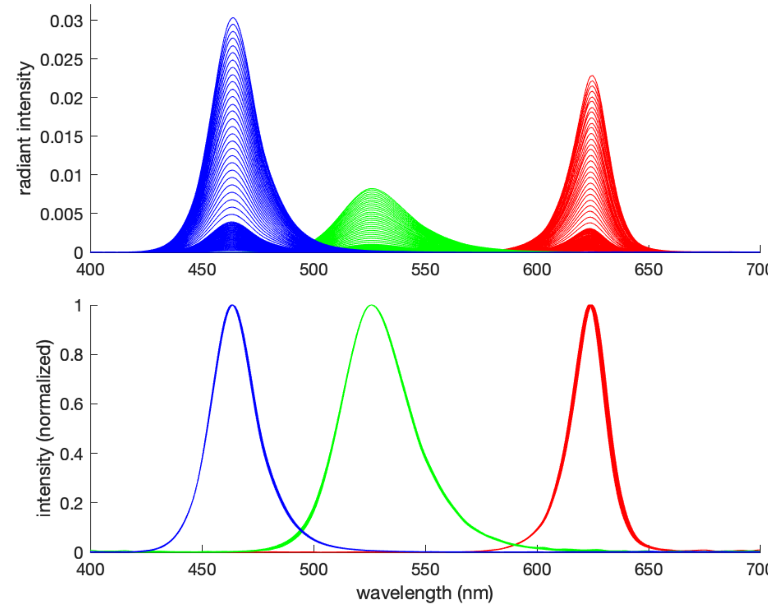
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

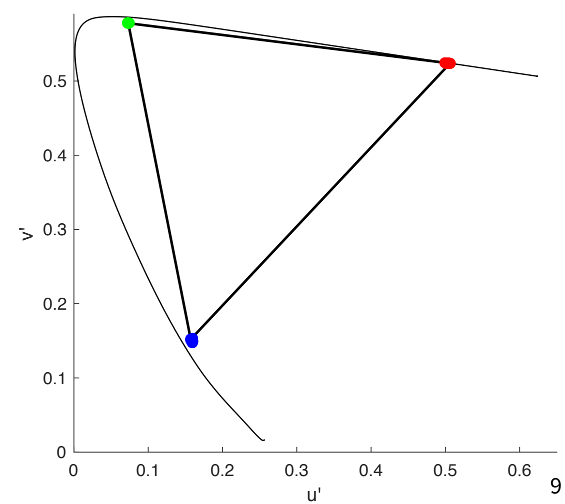
Additivity Assumptions

- Spectral stability (constant chromaticity)
- Channel independence
- Separability of nonlinearity
- Constant offset

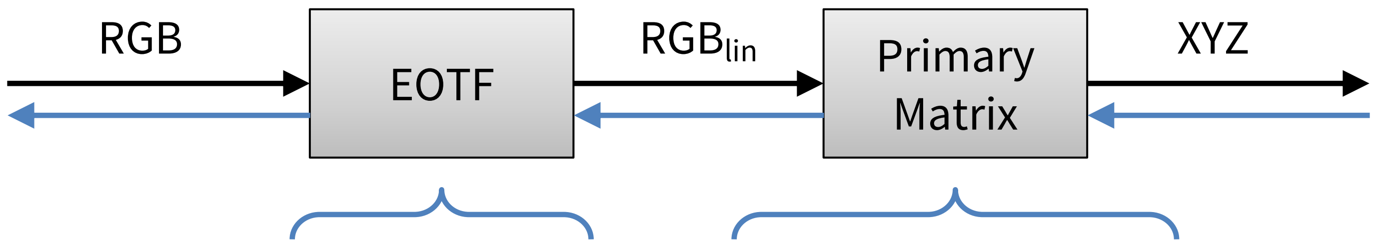
$$S(\lambda) = \sum_{i=1}^{n} p_i \, S(\lambda)_i + S(\lambda)_{flare}$$

$$p_{i,linear} = f\left(p_{i,encoded}\right)$$





General Additive Colorimetric RGB Model



LUT or function

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \mathbf{M} \begin{bmatrix} R \\ G \\ B \end{bmatrix}_{lin} + \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{flare}$$

- Primary matrix $\mathbf{M}$: XYZ of individual R, G, B channels
- 3x3 matrix $\mathbf{M}$ is invertible
- “Flare” is non-zero black level
- Model assumes: Channel independence & scalability

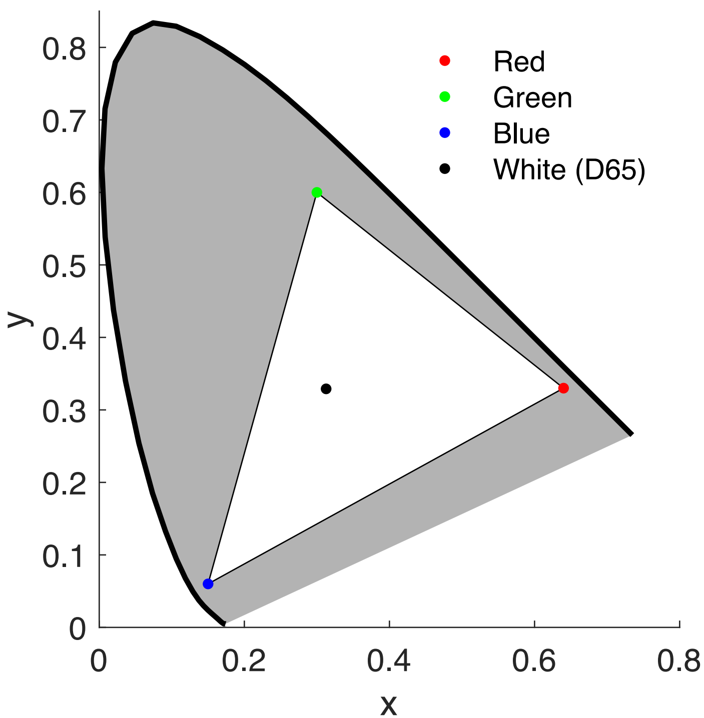
An Idealized Display: sRGB

- sRGB "Standard" RGB
- Defined in 1999 by International Electrotechnical Commission (IEC 61966-2-1) & previously (1996) by the W3C
- Defines:
  - Display white point: D65, CIE x,y (0.3127, 0.3290), 80 cd/m^2
  - Color primaries: RGB CIE x,y (0.64, 0.33), (0.30, 0.60); (0.15, 0.06)
  - EOTF: piecewise function similar to $y = x^{2.2}$
  - Viewing conditions: 4 cd/m^2 D50 surround

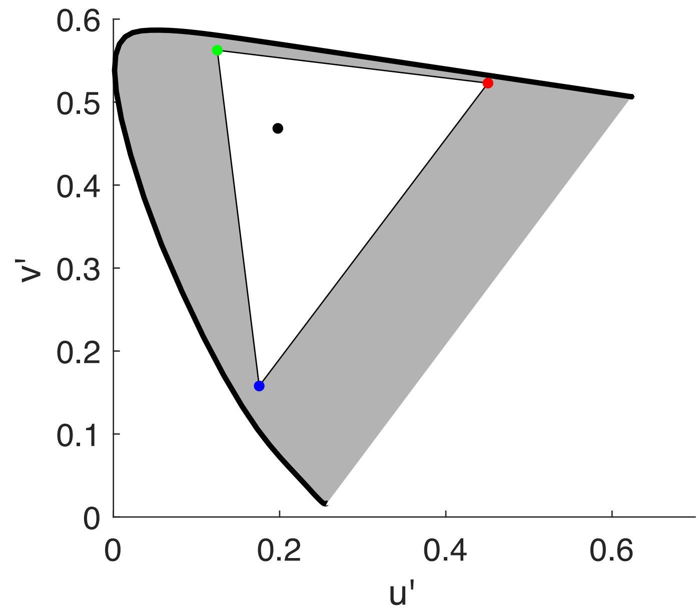
W3C sRGB: https://www.w3.org/Graphics/Color/sRGB.html
IEC 61966-2-1: https://webstore.iec.ch/publication/6169

An Idealized Display: sRGB Primaries

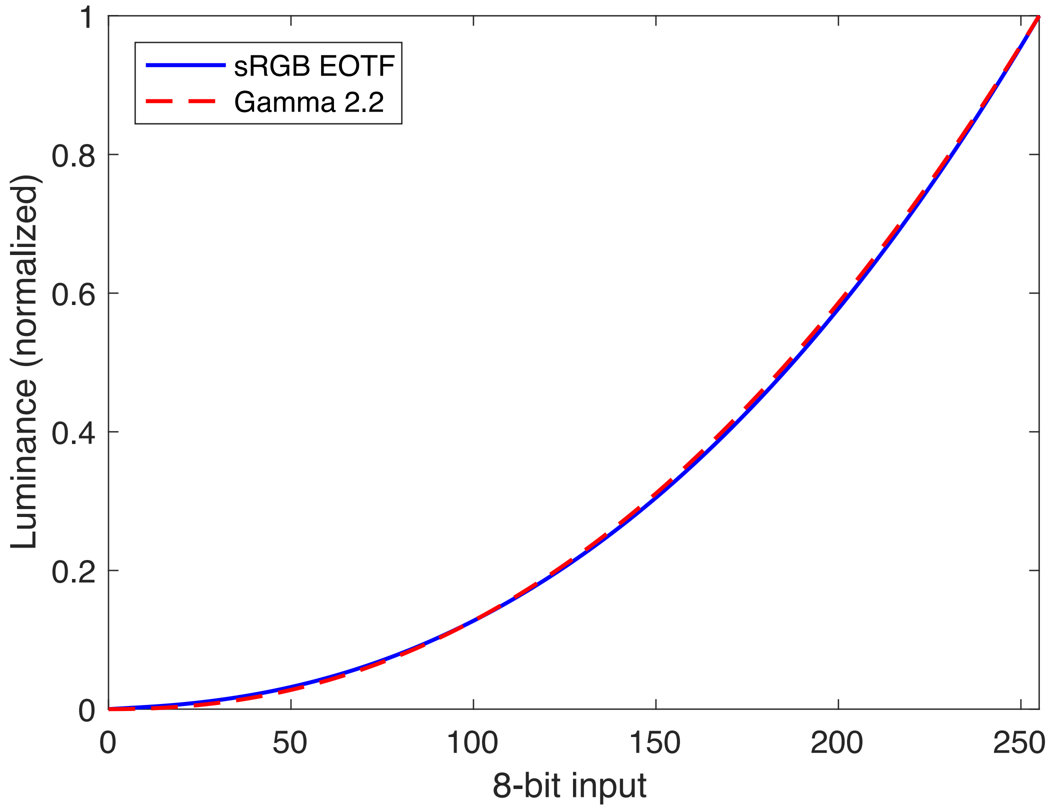
CIE 1931 xy (nonuniform!)



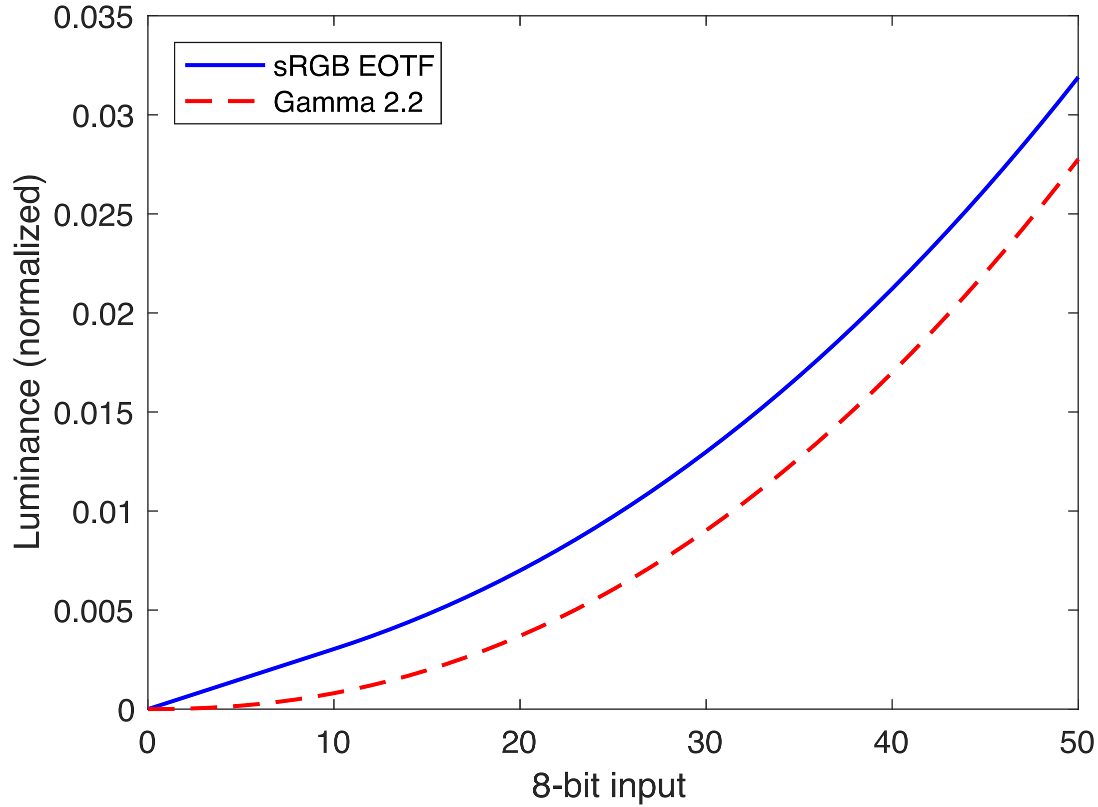
CIE 1976 u'v' (better!!)



An Idealized Display: sRGB EOTF

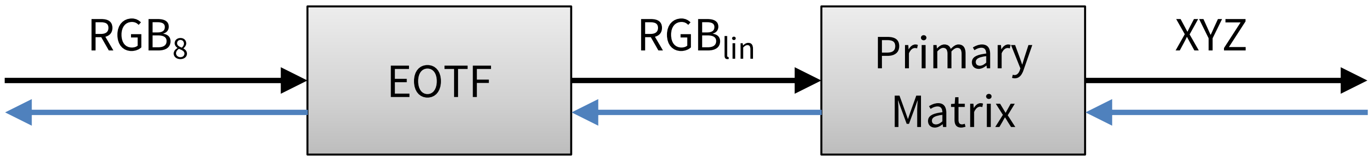


An Idealized Display: sRGB EOTF



An Idealized Display: sRGB

- Deterministic colorimetric output (CIE XYZ) for any RGB input



- Color gamut is well-defined (additive)
- And also: black = ZERO

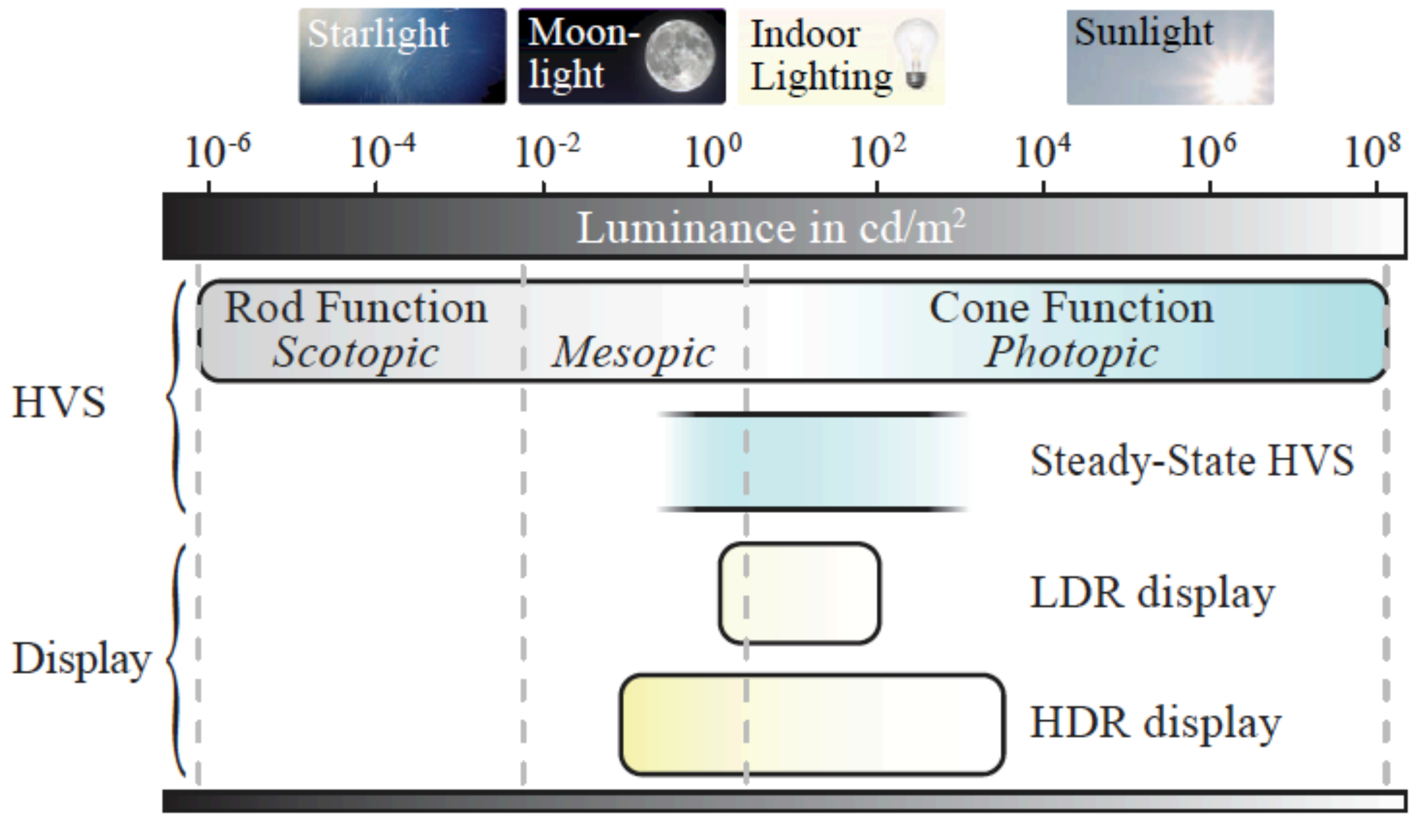
- sRGB is ubiquitously used as a color image encoding: JPG, www

Real-World sRGB

- Much higher white point (200-300 cd/m^2 instead of 80)
- Decent consumer monitors match primaries and relative EOTF
- BUT black is not zero!
- Viewing conditions??

Dynamic Range

Luminance Dynamic Range



Dynamic Range
Ymax/Ymin or
log(Ymax/Ymin)

aka Contrast Ratio
(Ymax/Ymin):1

Figure 1 from Kunkel & Reinhard, A Reassessment of the Simultaneous Dynamic Range of the Human Visual System, ACM APGV 2010: https://doi.org/10.1145/1836248.1836251

Display Types and Dynamic Range

Emissive displays:

- (CRT, Plasma)
- OLED, LED-walls

- Light is generated at each pixel as needed

- Typically limited at high end

Light-filtering displays:

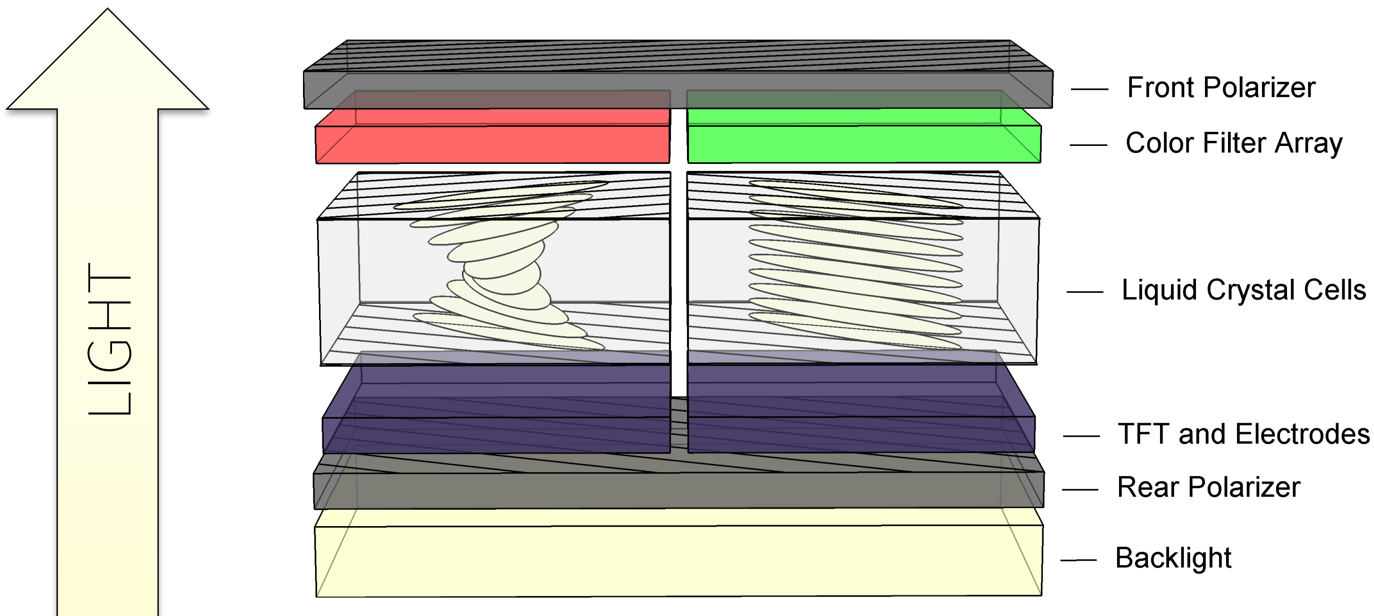
- LCD flat panels
- LCD & DLP projection
- Reflective LCDs, eInk

- White light source is attenuated by pixels

- Typically limited at low end

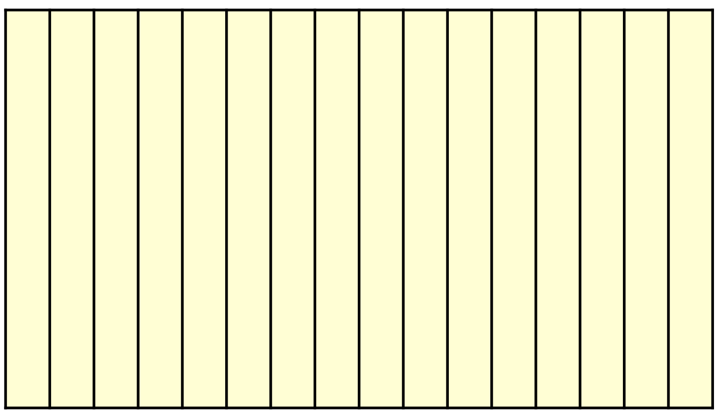
LCD: Liquid Crystal Display

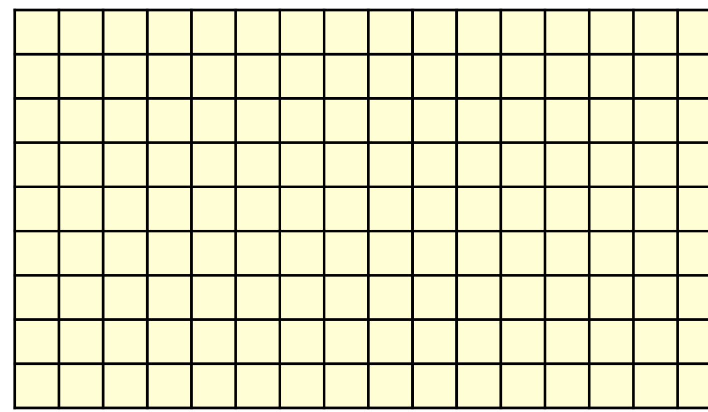
- A light valve at each pixel, max attenuation ~1000:1



HDR LCDs

- Getting past the 1000:1 limitation
- Spatially-addressable backlight, much lower than pixel resolution (i.e. 16 columns or 16x9 blocks):



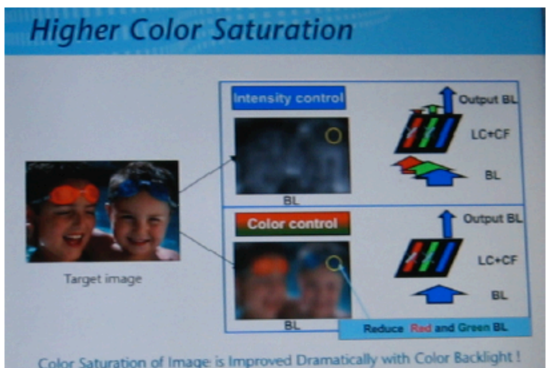


Dynamic contrast-local

AUO :

High Dynamic Contrast

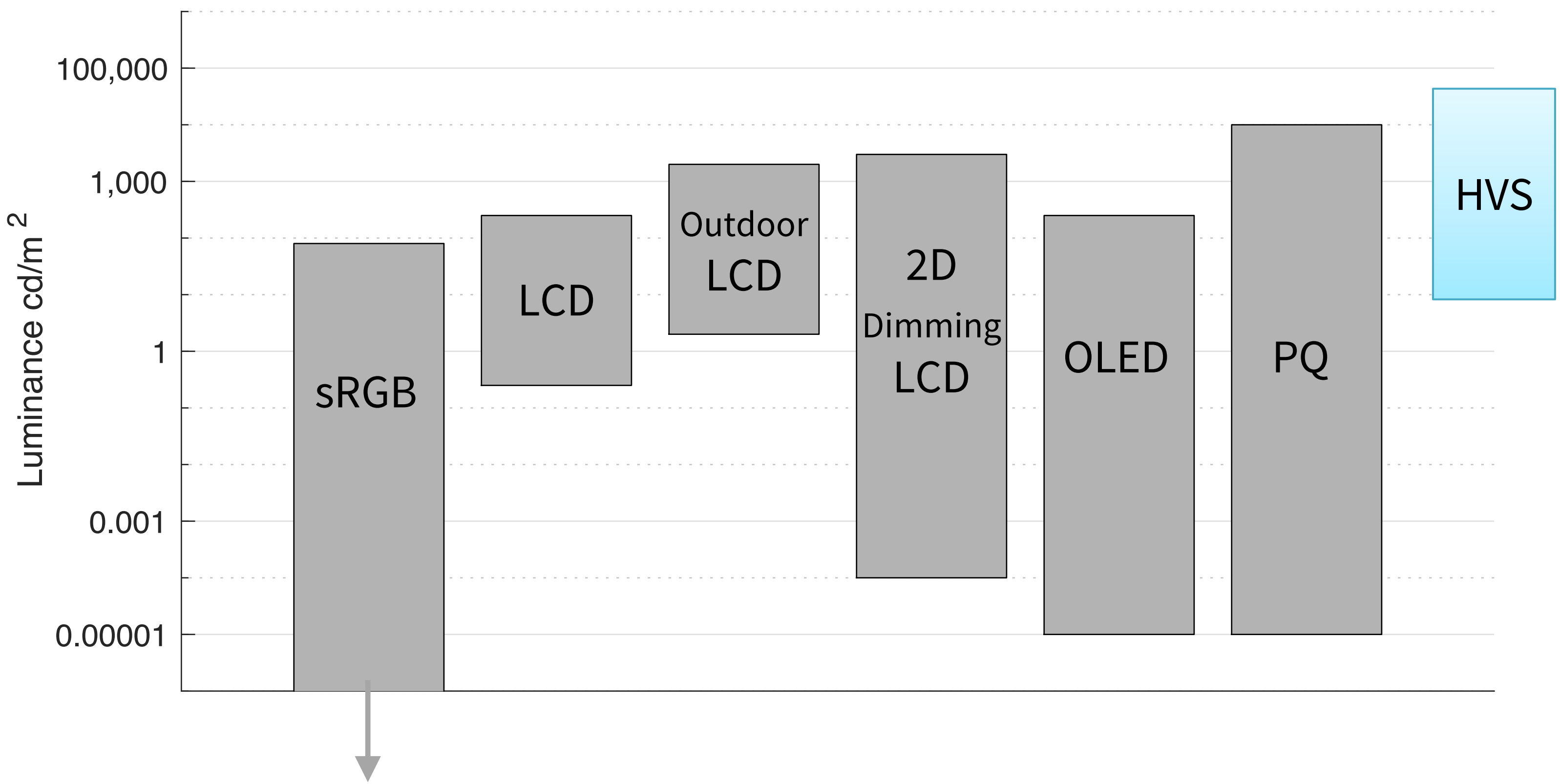
with local dimming



Improved color saturation

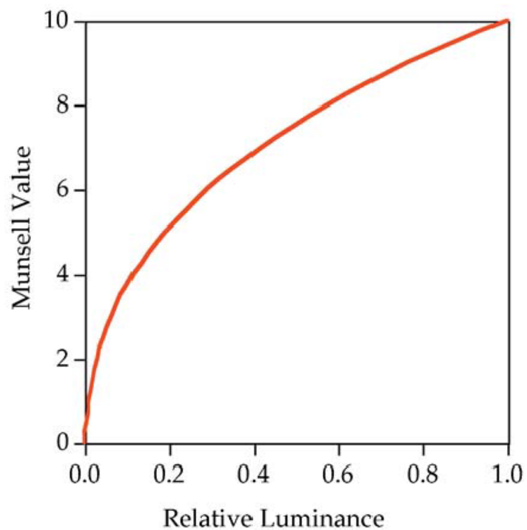
Color Imaging Conference 2019, Color Optimization for Displays, Gabriel Marcu, Copyright 2019

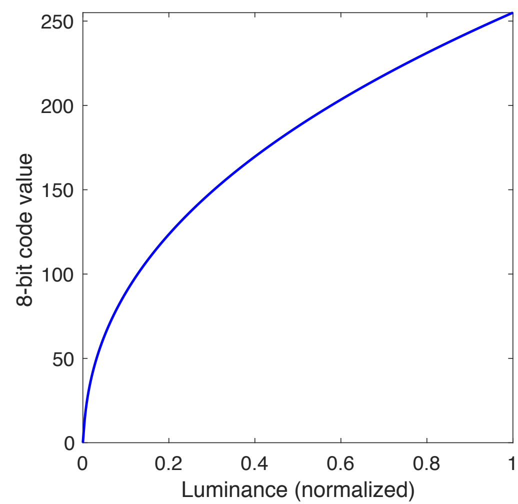
Luminance Dynamic Range



EOTF & EOTF^{-1} for Encoding

- EOTF allows perceptually-efficient use of bit depth
- This is a lucky coincidence: lightness perception nearly matches a CRT's EOTF^{-1}





Left: Fairchild, Color Appearance Models 3ed, Wiley (2013): http://doi.org/10.1002/9781118653128

EOTF & EOTF^{-1} for Encoding

- DICOM[1]: 10-bit EOTF for monochrome radiographic displays
- HDR EOTFs:
  - Perceptual Quantizer (PQ)[2]: “stacked” JNDs from 10,000 cd/m^2 down, over 10 or 12 bits (HDR10, Dolby Vision)
  - Hybrid Log-Gamma (HLG)[3]: piecewise function extending SDR “gamma” curve with logarithmic compression

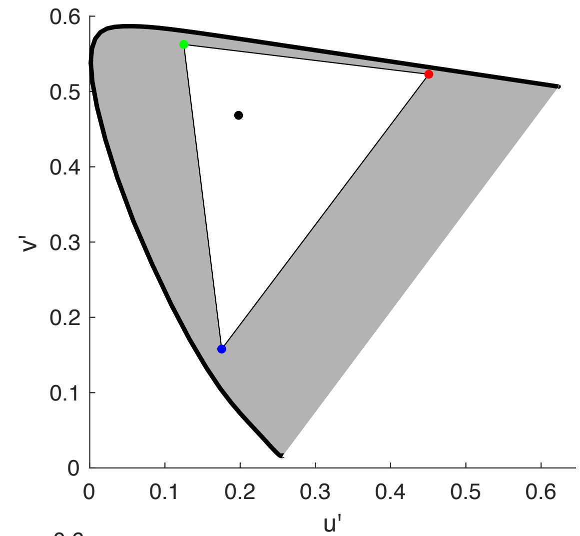
1: DICOM PS 3.14-2011 Part 14: Grayscale Standard Display Function: http://dicom.nema.org/Dicom/2011/11_14pu.pdf
2: ST 2084:2014 - SMPTE Standard - High Dynamic Range Electro-Optical Transfer Function of Mastering Reference Displays: http://doi.org/10.5594/SMPTE.ST2084.2014
3: ARIB STD-B67, Essential Parameter Values For The Extended Image Dynamic Range Television (EIDRTV) System For Programme Production (2015): https://www.arib.or.jp/english/html/overview/doc/2-STD-B67v1_0.pdf
See Also: SMPTE Report: https://www.smpte.org/sites/default/files/Study%20Group%20On%20High-Dynamic-Range-HDR-Ecosystem.pdf

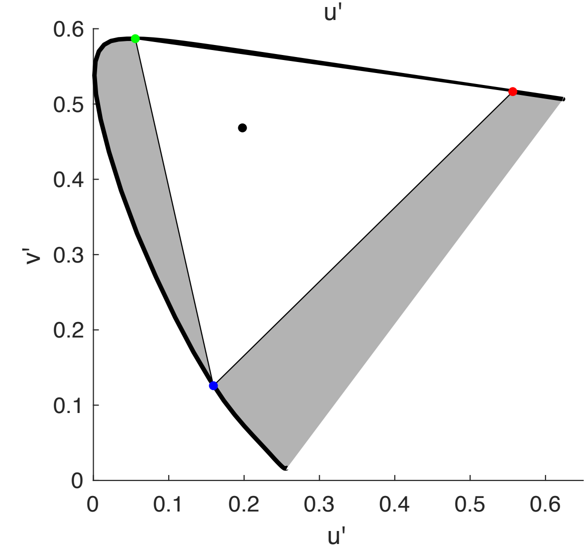
Color

RGB Primary Selection

"Wider Gamut" RGB →

- Larger chromaticity gamut (triangle)
- Larger gamut volume?
- Different luminance distribution (G higher, B/R lower)
- Higher quantization potential (bit depth dependence)
- More inter-observer variation (observer metamerism)

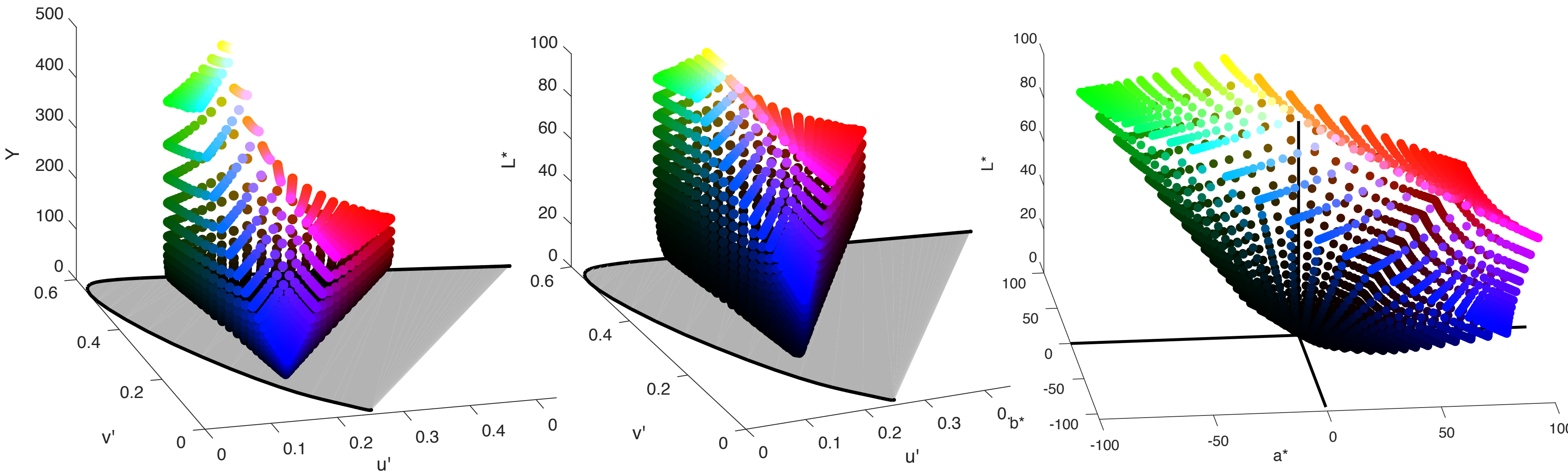




Color Gamut is 3D

However, no real agreement on Z-axis; thus no volume measure

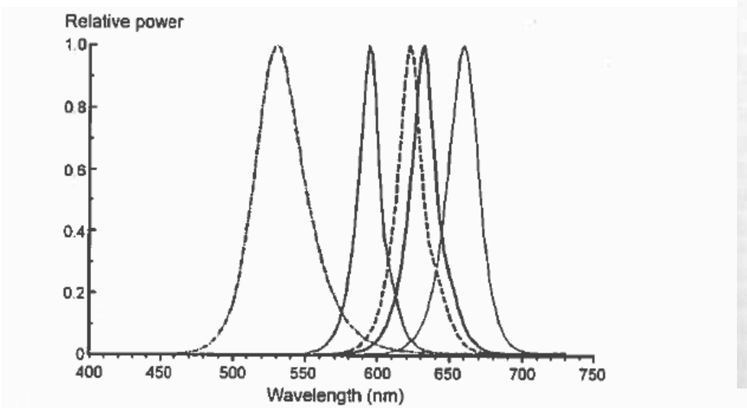
Below: u’v’Y, u’v’L*, a*b*L*:

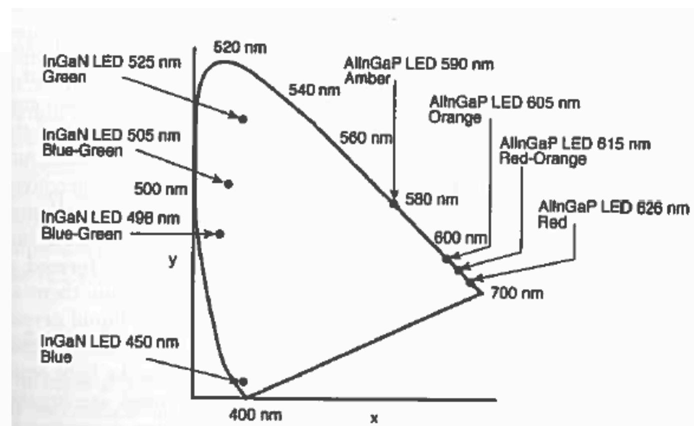


Mechanisms for Color

Emissive displays:

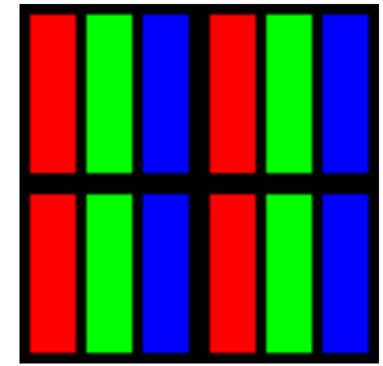
- LED & OLED electroluminescence (electron → photon): chemical structure / dopants tune the energy of the band gap (bluer is higher energy, redder lower energy)





Boyce, Peter Human Factors in Lighting, Taylor & Francis (2003): https://www.taylorfrancis.com/books/9780203426340

Mechanisms for Color

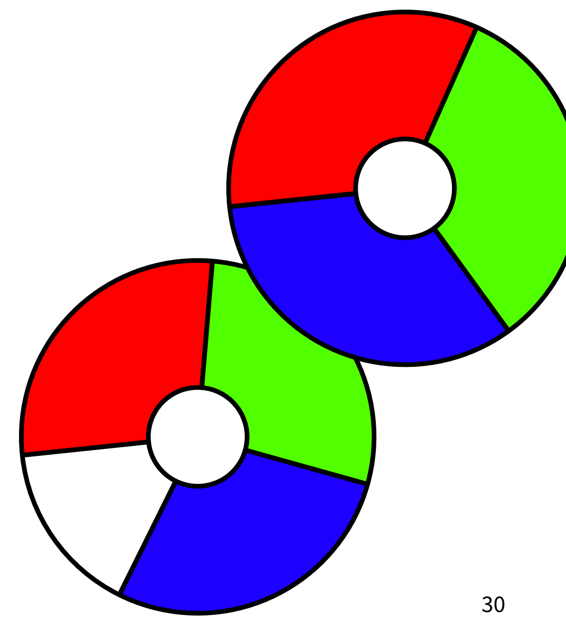


Light-filtering displays:

- “White” light source: CCFL, LED (RGB or PC) + Color filter array
- RGB LEDs, sequential color

Projection:

- Halogen, Xenon, Laser (RGB or PC) + Color filters (separate imagers) OR color filter wheel (sequential color)
- RGB LEDs, sequential color

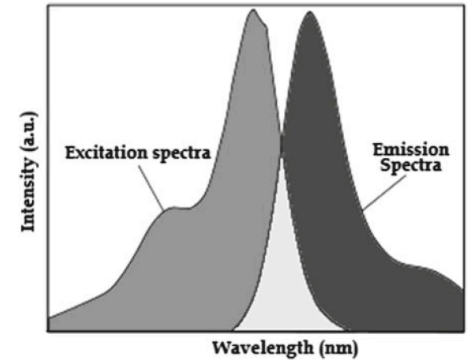


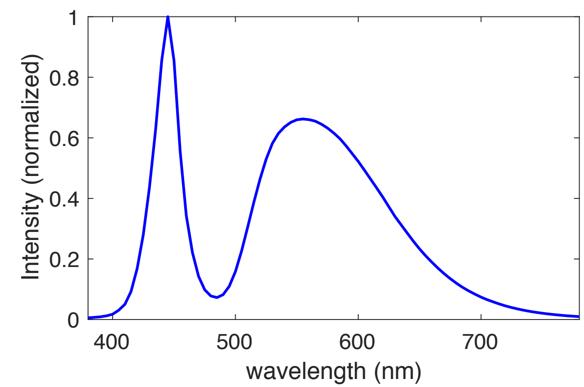
Mechanisms for Color

Phosphors:

- Fluorescent materials: absorb photons, emit lower-energy photons
- Phosphor-converted (PC) white LEDs: blue LED + yellow phosphor

- Quantum Dots: narrow emission bandwidth determined by size of nano-sphere of shells of ZnS, CdSe, PbS, etc.



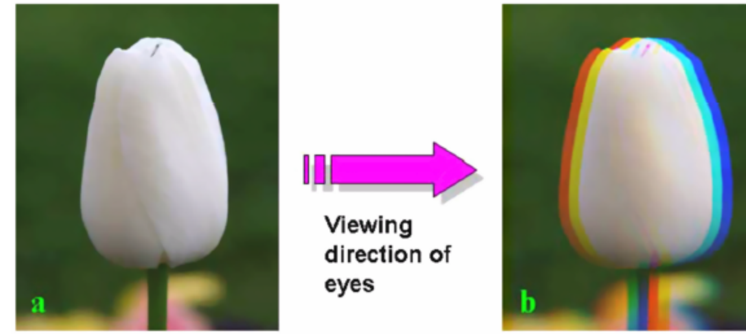


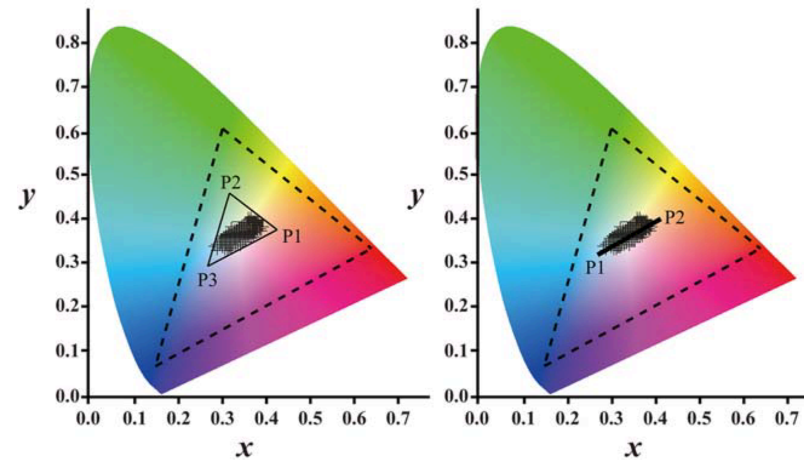
Shinde et al., Phosphate Phosphors for Solid-State Lighting, Springer (2013): http://doi.org/10.1007/978-3-642-34312-4

Mechanisms for Color

Sequential color:

- Very high efficiency (no color filters)
- Color break-up, especially with moving content or moving eyes
- RGB or RGBW
- Optimized 2+ frame subfields via mixes of RGB primaries





Wang et al., Color breakup visibility thresholds for 2-field sequential colors, CR&A, 2017: http://doi.org/10.1002/col.22125
Huang et al., Suppressing color breakup in LCDs, SPIE Newsroom, 2008: http://doi.org/10.1117/2.1200808.1254
See also: Mineo et al., Mechanism of color breakup in field-sequential-color projectors, JSID, 7(4), 1999.

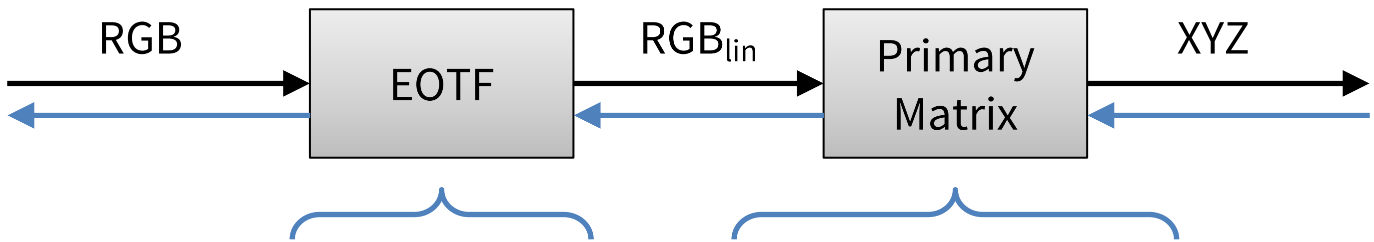
Display Characterization

Measurement, Characterization, Calibration

- **Measurement**: spectral or colorimetric measurement from perspective of viewer[1]
- **Characterization**: measure & build a model (e.g. LUT, M, flare), allowing predictable behavior via device-dependent RGB[2,3]
- **Calibration**: adjust display behavior to match a standard, to allow direct use of standard RGB (change ICC or built-in LUTs)
  - Calibration pucks
  - Self-calibrating displays

1: SID ICDM Information Display Measurement Standards https://www.icdm-sid.org/downloads/index.html
2: Fairchild & Wyble, Colorimetric characterization of the Apple studio display (Flat panel LCD), RIT 1998: http://scholarworks.rit.edu/article/920/
3: Berns, Methods for Characterizing CRT Displays, Displays (1996): https://doi.org/10.1016/0141-9382(96)01011-6

General Additive Colorimetric RGB Model



LUT or function

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \mathbf{M} \begin{bmatrix} R \\ G \\ B \end{bmatrix}_{lin} + \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{flare}$$

- Primary matrix **M:** XYZ of individual R, G, B channels
- 3x3 matrix **M** is invertible
- “Flare” is non-zero black level
- Model assumes: Channel independence & scalability/additivity

Model Assumptions

- Three channels or primaries (R G B)
- Channel independence (aka additivity)
- Constant chromaticity primaries (aka spectral scalability)
- Constant black level (linear offset)

- Stability

All displays have…

- Image input specifications / encodings
- Tone characteristics: Electro-optical transfer function (EOTF)
- Color characteristics (primaries, gamut, additivity)
- Calibration state
- Dynamic behavior / algorithms
- Viewing environment effects (physical and perceptual)

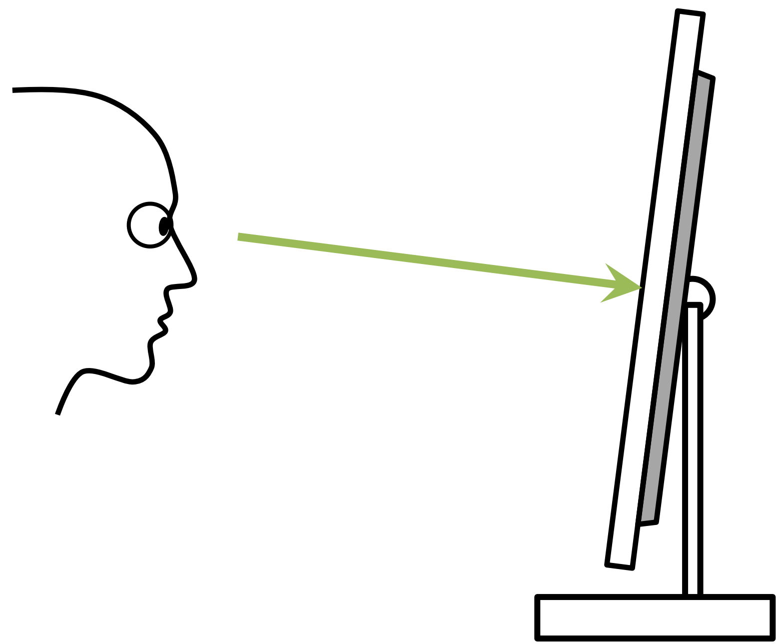
Turn off

- Screen saver & power saver
- Automatic brightness settings
- Automatic color settings: NightShift, f.lux, TrueTone, etc.

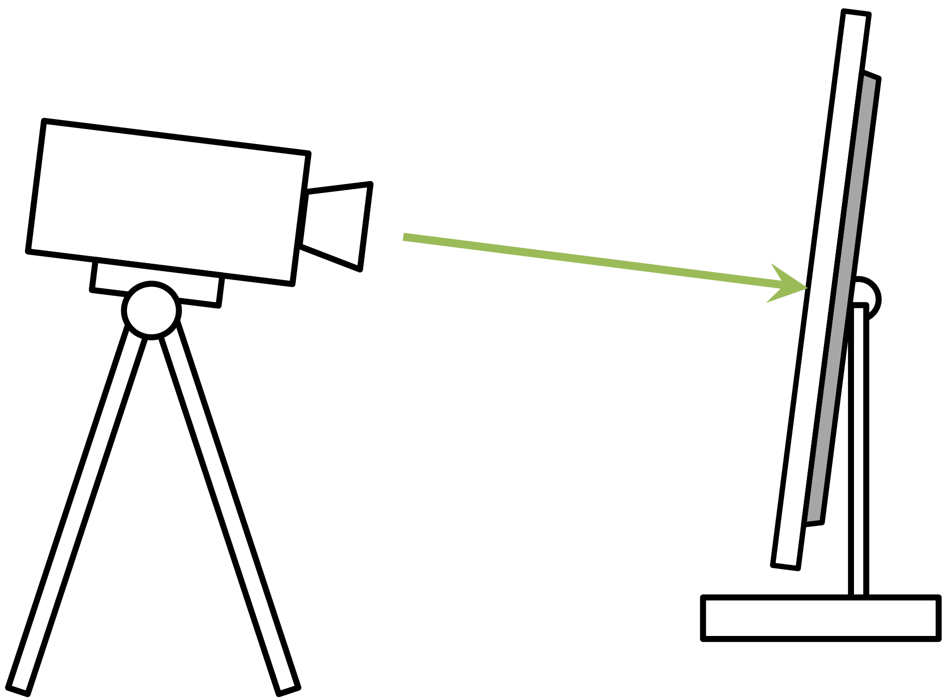
Warm up

30-120 minutes for a display to stabilize

Measurement in place of viewer



Measurement in place of viewer



Also consider

- Operating system settings
- Color management settings
- Program-specific settings

- If our experiment will use MATLAB, best to measure using MATLAB to generate the color samples

Measurement loop

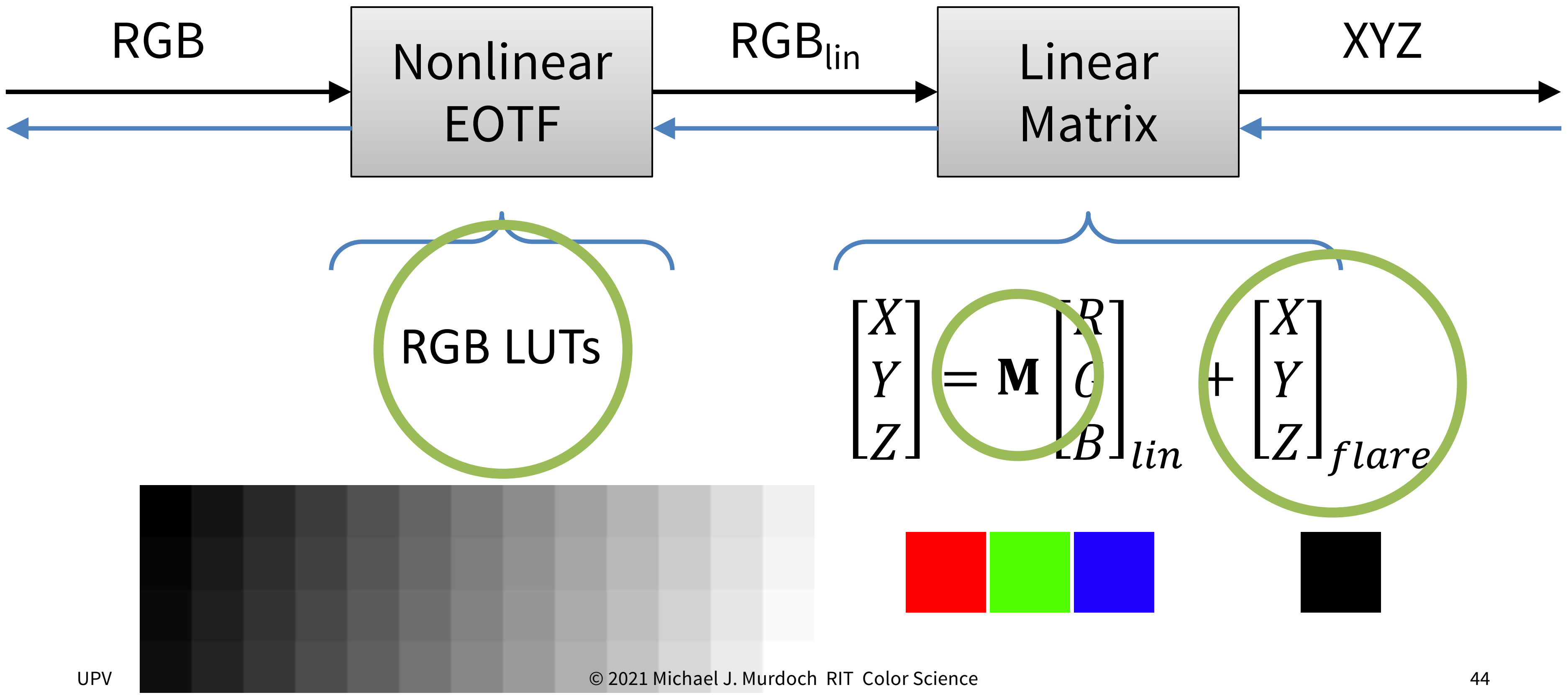
- Load *N* RGB code values
- Loop over *i* to *N*:
  - Set screen to color *i*
  - Measure
- Save data and build model

Characterization

- Measurements to build a model
- Measurements to verify the model

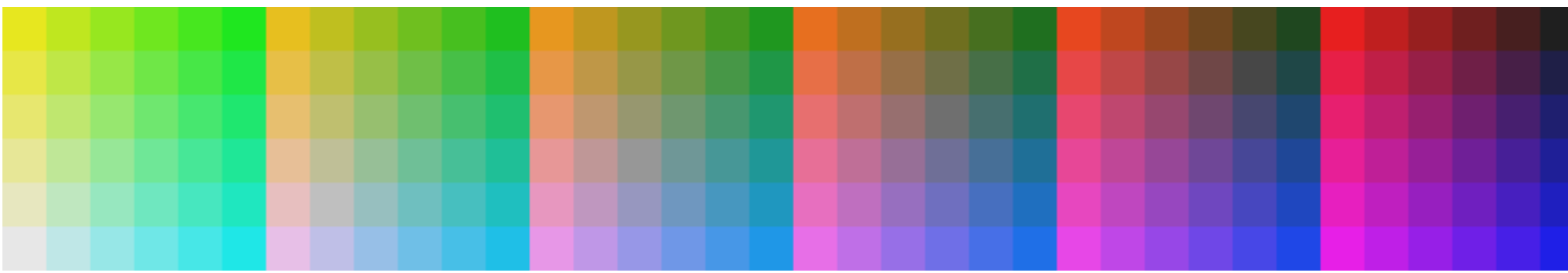
- ALSO: Check assumptions (see 1998 Fairchild & Wyble paper)

Measurements for the model components

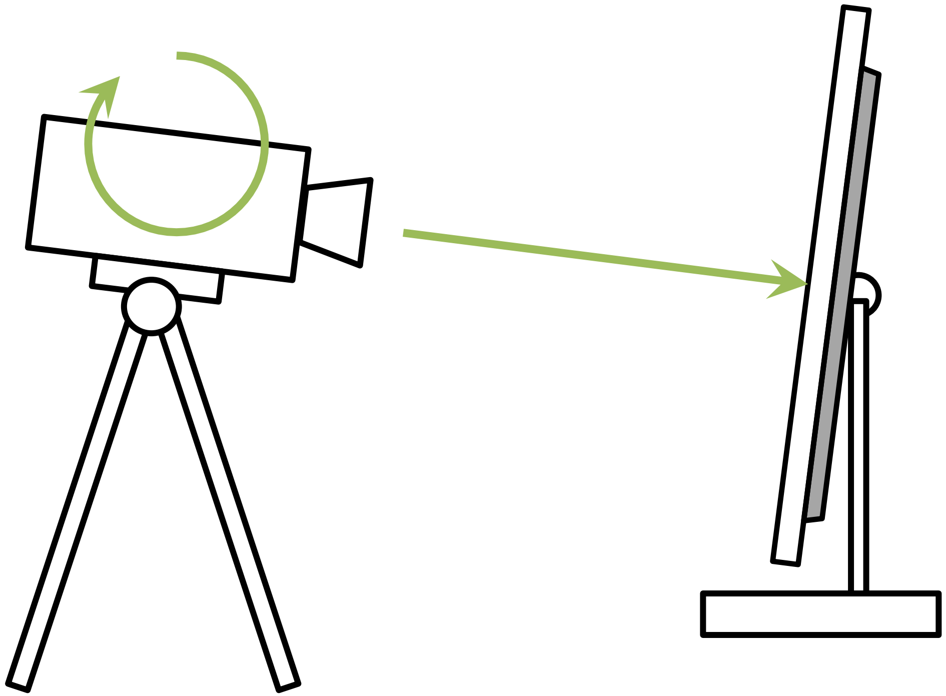


$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \mathbf{M} \begin{bmatrix} R \\ G \\ B \end{bmatrix}_{lin} + \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{flare}$$

Measurements for verification



Measure everything



Primary matrix

- The linear matrix **M**
- Three columns are black-subtracted XYZ of red, green, and blue

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \mathbf{M} \begin{bmatrix} R \\ G \\ B \end{bmatrix}_{lin} + \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{flare}$$

Neutral ramp to LUT

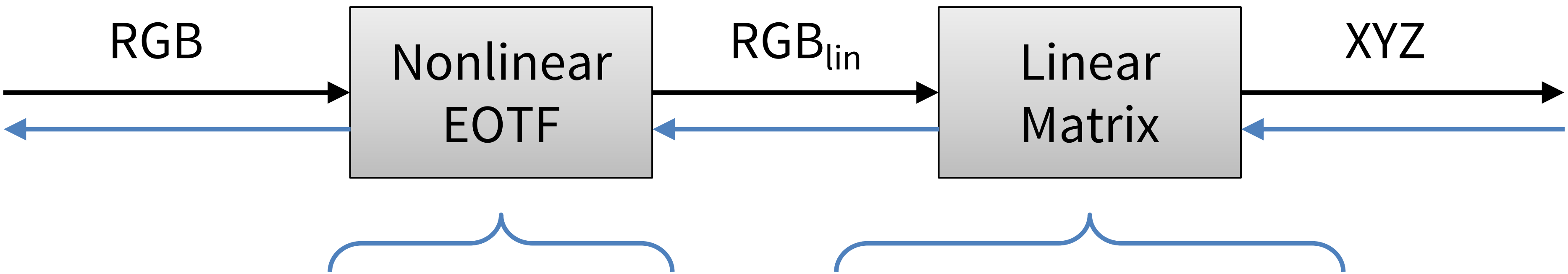
- Neutral ramp XYZ measurements must be converted to RGB intensity

- We compute the linear RGB intensity of each measured neutral ramp (black-subtracted) XYZ

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \mathbf{M} \begin{bmatrix} R \\ G \\ B \end{bmatrix}_{lin} + \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{flare}$$

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix}_{lin} = \mathbf{M^{-1}} \left(\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} - \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{flare} \right)$$

Model Implementation

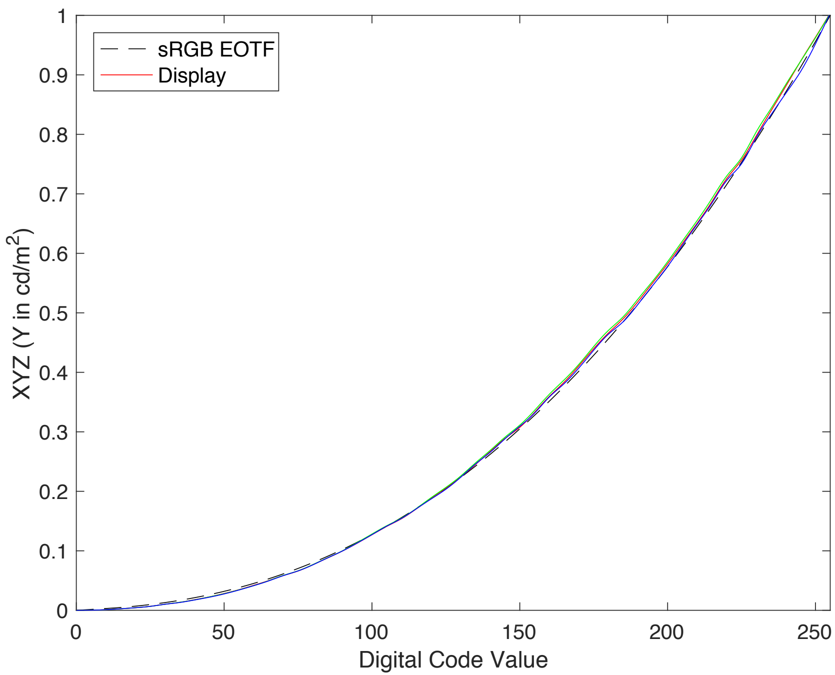


RGB LUTs

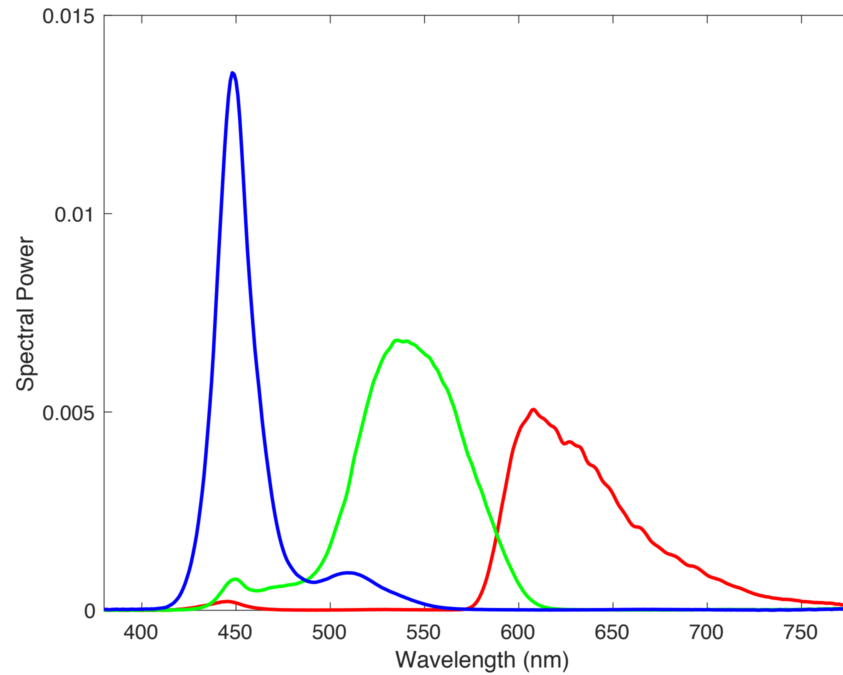
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \mathbf{M} \begin{bmatrix} R \\ G \\ B \end{bmatrix}_{lin} + \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{flare}$$

My Laptop Display → LUT + Matrix Model

EOTF



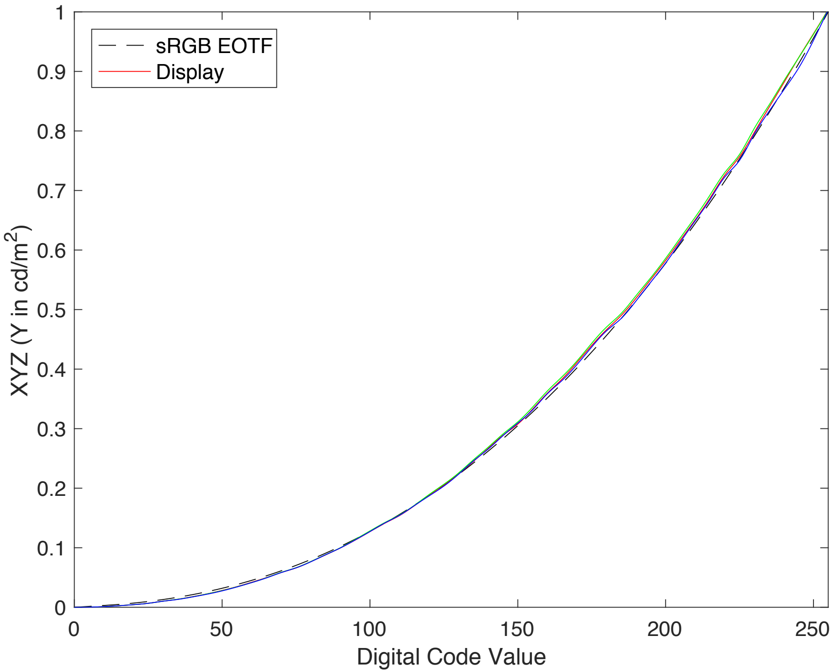
RGB SPDs



My Laptop Display

Black:	0.486	0.475	0.823
White:	359	375	440

EOTF



$$M: \begin{bmatrix} 152 & 131 & 74.7 \\ 78.5 & 267 & 26.7 \\ 5.72 & 42.7 & 389 \end{bmatrix}$$

Verification:

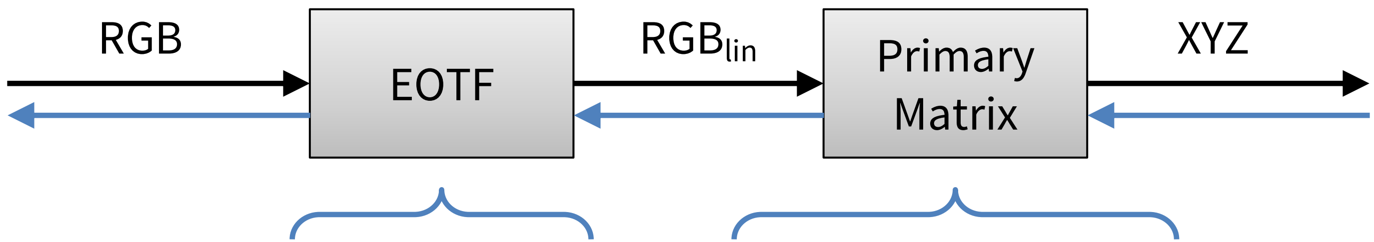
Median: 0.22 ΔE_{00}

Mean: 0.28 ΔE_{00}

Max: 1.06 ΔE_{00}

Advanced Displays

Breaking the General RGB Model



LUT or function

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \mathbf{M} \begin{bmatrix} R \\ G \\ B \end{bmatrix}_{lin} + \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{flare}$$

- Extra primaries (W, C, Y, etc.): $\mathbf{M}$ is not invertible
- Power limiting: non-additivity
- 1D or 2D dimming backlight: ~ per-pixel gain adjustment
- Display color processing: PFAs

Other Display Models

(In case of failure of LUT + Matrix model)

In general, other models require:

- More characterization data & storage
- Iterative inversion (possibly stored)

Options

- Blend of Matrices
- 1-D LUTs only (still assumes additivity)
- Empirical 3D-LUT (assumes nothing!)
- …

RGBW: Extra Degree of Freedom

Two options:

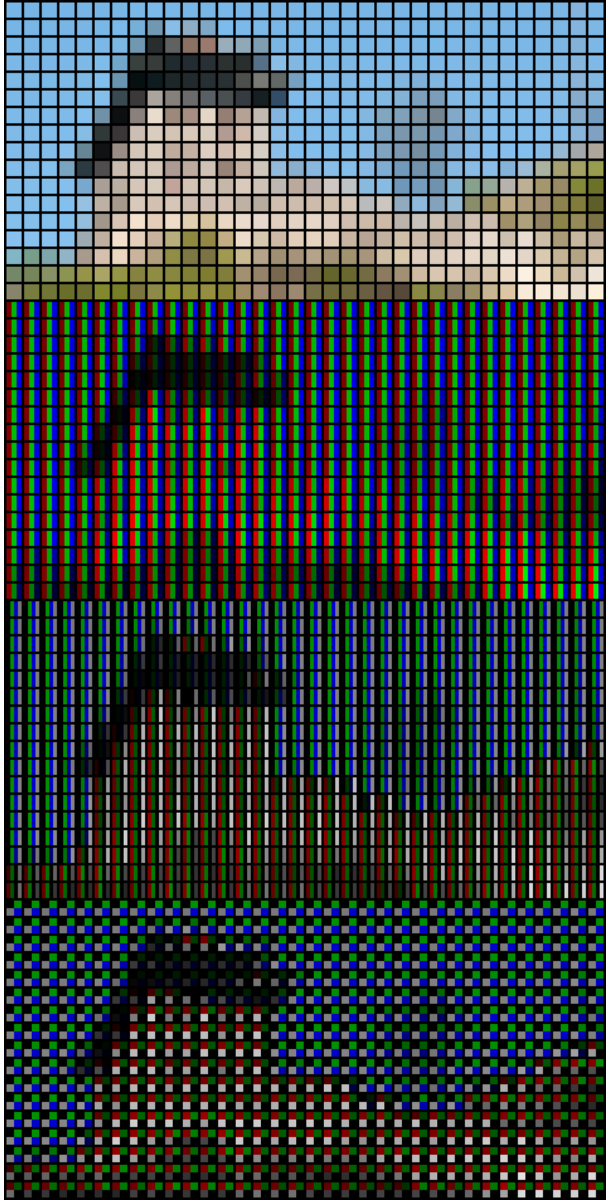
- Add W for luminance boost (trade away color gamut and color fidelity, common in projectors)
- Use W in place of RGB (improve power efficiency, especially in OLED)

Full Color

RGB stripe

RGBW stripe (W replacement)

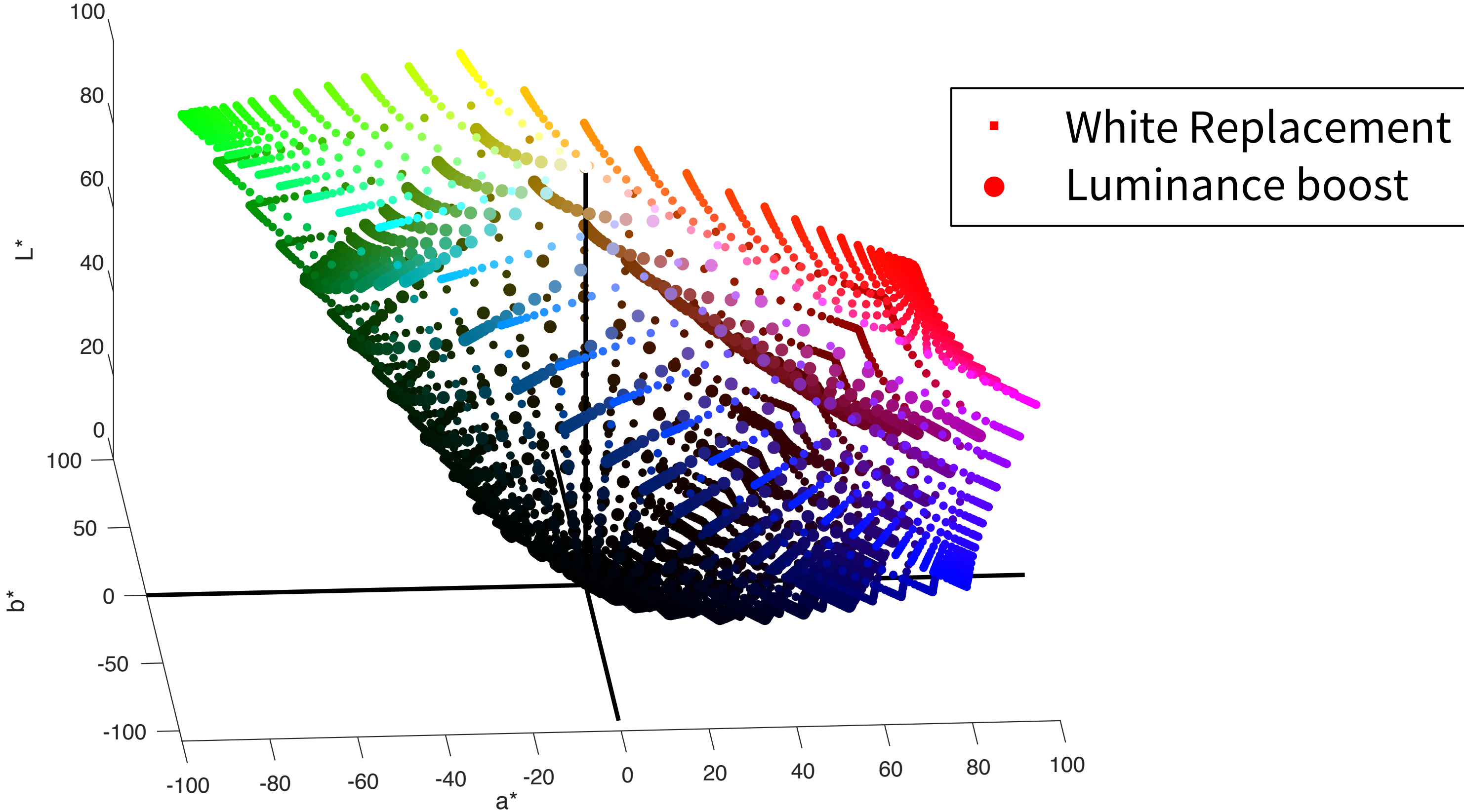
RGBW quad (W replacement)



Murdoch et al., Perfecting the color reproduction of RGBW OLED, ICIS 06.
Miller & Murdoch, RGB-to-RGBW conversion with current limiting for OLED displays, JSID 2009: https://doi.org/10.1889/JSID17.3.19

RGBW: Breaking the General RGB Model

- Gamut volume changes shape…

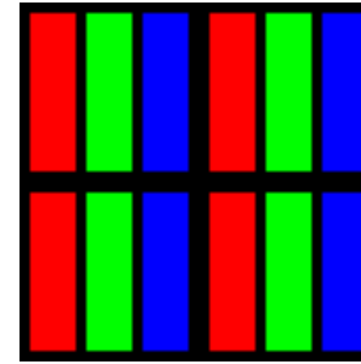


Multi-primary Color

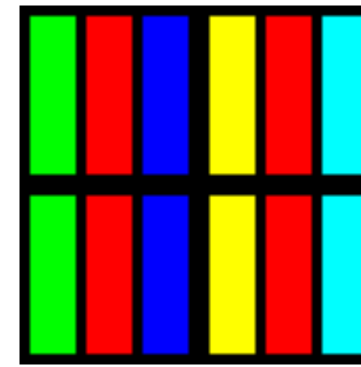
- Chromaticity gamut increase
- Primaries beyond RGB give extra degrees of freedom

- Spatial layout can reduce resolution
- Sub-pixel interpolation even more important than with RGB: smart spatial luminance distribution

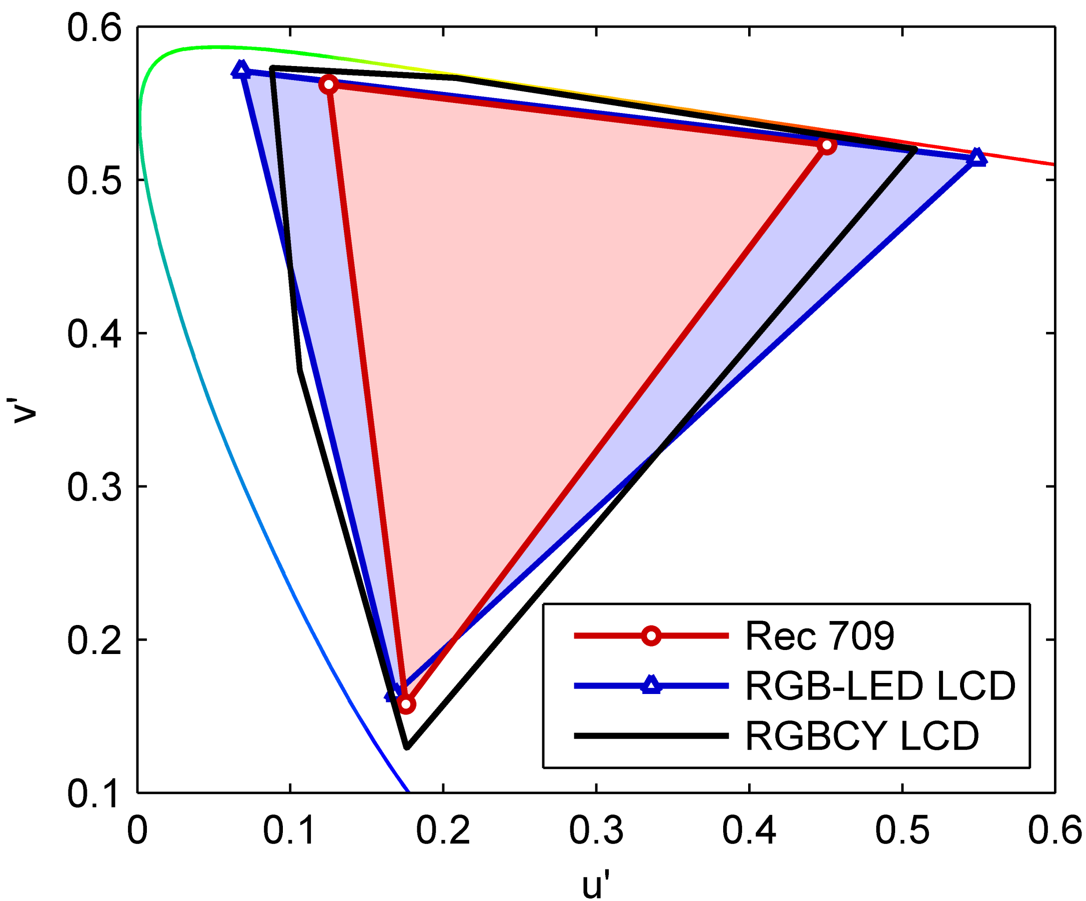
RGB
4 logical pixels



RGBCY
2(?) logical pixels



Multi-primary Chromaticity Gamut

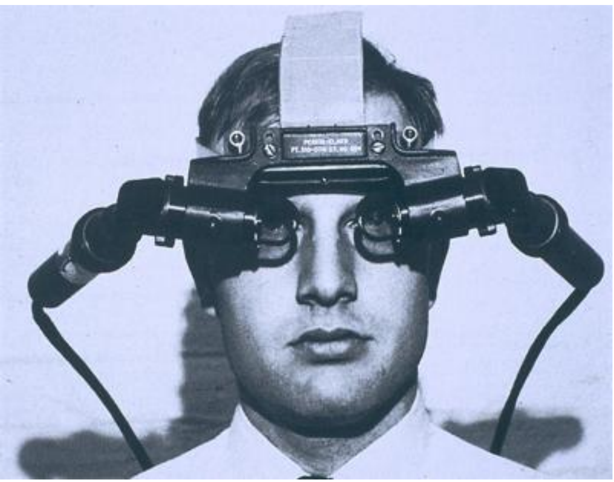


VR Displays

- LCD or OLED + optics
- Displays similar limitations as in bigger LCD or OLED
- Lenses → chromatic aberration, distortion, resolution

https://homido.com/mini/

[Optical See-Through] Augmented Reality: Transparent Displays

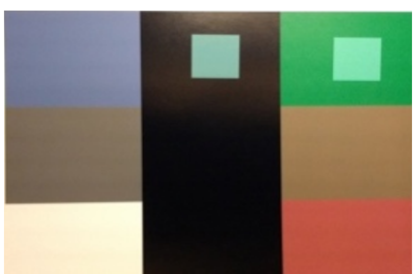

Sutherland et al. 1968

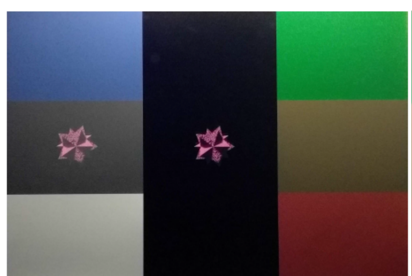

Microsoft HoloLens

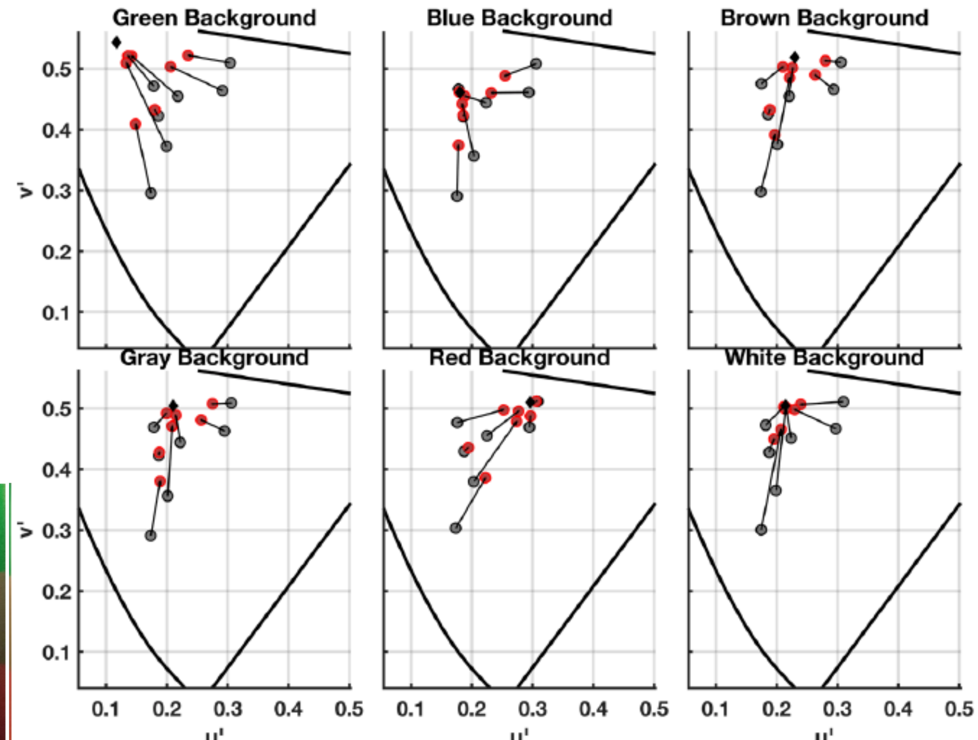

Meta 2

[Optical See-Through] Augmented Reality

- Real background + virtual foreground
- Background colors bleed through transparent display, distorting virtual colors
- Display model: flare++







LED Walls: Signage, Virtual Production

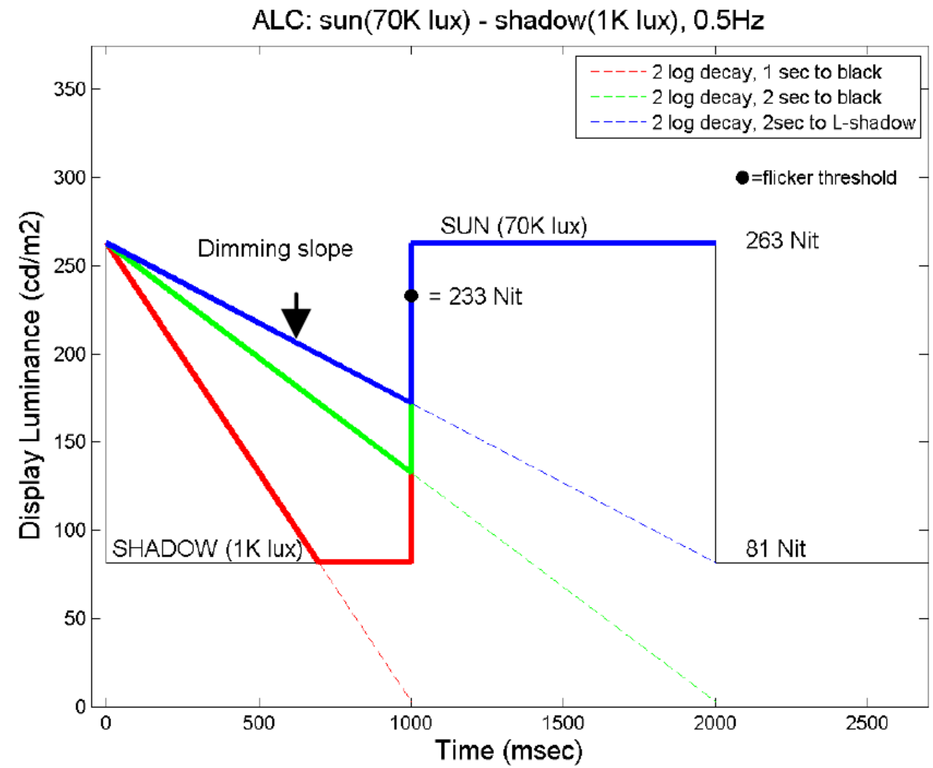
First Man, DNEG VFX: https://vimeo.com/317157759

Adaptive Displays

Adaptive Displays: Automatic Brightness Control

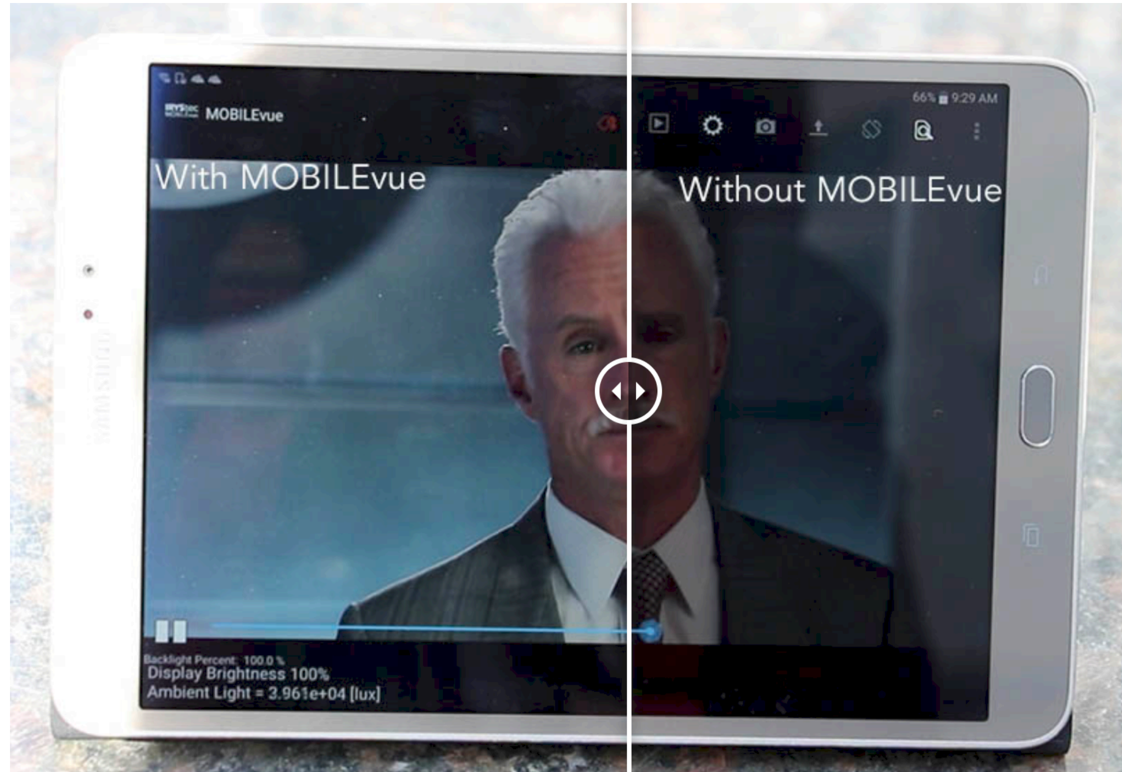
- Display white changes with ambient illumination
- Power savings
- 80:20 rule…

- Related to HVS luminance adaptation and camera auto-iris



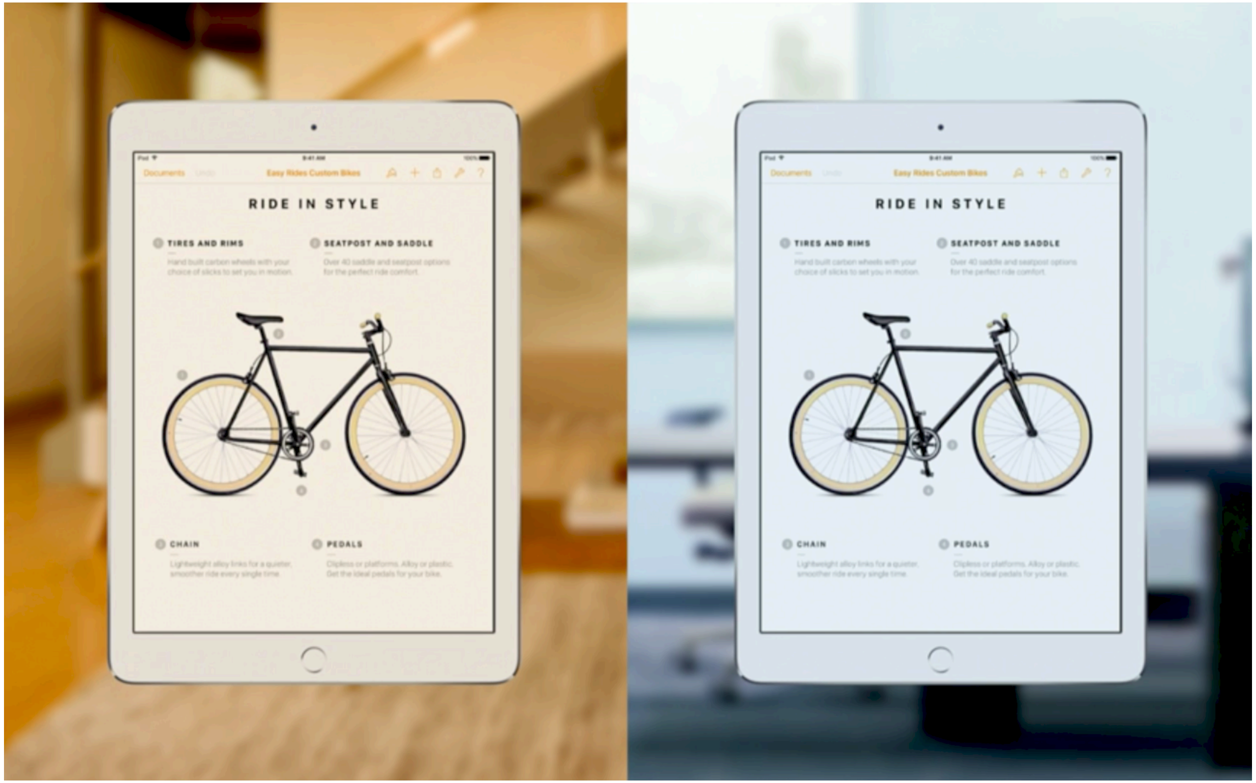
Swinkels et al., Ambient Light Control for Mobile Displays, SID, 2008: https://doi.org/10.1889/1.3069301
See also: Merrifield and Silverstein, The ABC's of automatic brightness control, SID, 1988.

Adaptive Displays: Brightness and Tonescale



Apple iPhone X via TechCrunch: https://techcrunch.com/gallery/12-neat-hidden-features-in-iphone-x/
IRYStec's Perceptual Display Platform (PDP): http://www.irystec.com/

Adaptive Displays: White Point



Apple TrueTone example, MacWorld: https://www.macworld.com/article/3055407/ios/how-to-make-night-shift-act-more-like-true-tone.html

Adaptive Displays: White Point

Blue reduction: examples f.lux, Night Shift, etc.

Apple TrueTone example, MacWorld: https://www.macworld.com/article/3055407/ios/how-to-make-night-shift-act-more-like-true-tone.html

Thank you!

Michael J. Murdoch
Munsell Color Science Laboratory
mmpocs@rit.edu
mcsl.rit.edu