Lecture 22: Display Technologies and Lightning Systems
Logistics

 › Programming assignment 2 released. Due 12/04.
 › Guest lecture by Adrian Sampson next Wednesday on graphics programming models.

 ▶ Real-time 3D graphics systems are everywhere, but the tools that software engineers use to build them are from the dark ages. OpenGL was invented in a time when GPUs were fixed-function pipelines, and it has grown haphazardly into a flexible system that resembles an inconvenient, confusing programming language. Essentially, it attempts to be both a convenient programming model and a portable hardware abstraction—and it does poorly at both. Modern APIs like Vulkan and Metal address the problem by acting *only* as low-level system abstractions, relegating the programming model to higher levels in the system stack. This shift creates an opportunity for research on designing programming models for real-time graphics that make it more expressive, faster, and more correct. In this talk, I will complain endlessly about OpenGL and then talk about two projects in my lab that aim to alleviate some of the misery it induces.
Where Are We?

Physical Scene (Objects, lights) → Optics (Gather light) → Image Sensing (Optical to electrical signal transformation) → Image Signal Processing (Signal reconstruction) → Computer Vision (Semantics understanding)

Optics (Gather light) → Modeling (Scene, optics) → Computer Graphics (Visibility + Shading) → Display (Generating lights) → Human Vision System (Eye, visual cortex) → Video/Image De/Compression → Cloud/Storage
Recall: Metamerism

- Two lights have different spectrums but are perceived as the same color as long as their LMS values match.

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\[
\int_{\lambda} \Phi_1(\lambda) L(\lambda) d\lambda = \int_{\lambda} \Phi_2(\lambda) L(\lambda) d\lambda
\]

\[
\int_{\lambda} \Phi_1(\lambda) M(\lambda) d\lambda = \int_{\lambda} \Phi_2(\lambda) M(\lambda) d\lambda
\]

\[
\int_{\lambda} \Phi_1(\lambda) S(\lambda) d\lambda = \int_{\lambda} \Phi_2(\lambda) S(\lambda) d\lambda
\]

Recall: Color Matching Experiments

![Diagram showing color matching experiments with wavelength (λ) ranging from 400 to 700 nm and two responses marked as ??, 435.8, 546.1, and 700 with an angular separation of 2°.]
Recall: Trichromatic Theory of Color and Color Space

https://en.wikipedia.org/wiki/CIE_1931_color_space
https://www.suntos.com.np/computer-vision-for-robotics/what-is-image.html
Trichromatic Theory of Color Has Huge Implications

› All color capturing and reproduction systems, e.g., display and cameras, fundamentally rely on it.

› **Camera**: to capture the color of a light, we just need to capture the “intensities” of three primary lights, rather than precisely capturing the SPD of the target light.

› **Display**: to reproduce the color of a light, we just need to mix three primary lights, instead of precisely generating the SPD of the light.
Apparent Color vs. Spectrum

The two lights have similar apparent color, but are they the same light?
Apparent Color vs. Spectrum

The two lights have similar apparent color, but are they the same light?

No! Due to metamerism, lights with the same apparent color could have very different spectrums.
Why Does Spectrum Matter? Color Rendering!

Assuming these two light sources are metamer, which one is better at revealing the color of the object with the given spectral reflectance?

https://socratic.org/questions/5a4d3c8b11f0b429b0b8c3
Why Does Spectrum Matter? Color Rendering!

- Color rendering concerns with the ability of a light source to reveal the “objective color” of an object (spectral reflectance).

Assuming these two light sources are metamers, which one is better at revealing the color of the object with the given spectral reflectance?

To reveal the true color of an object, the light source needs to emit wavelengths that the object reflects!

https://socratic.org/questions/5a4d3cdb11ef6b02f0bf08c3
Color Rendering Index

- CRI quantifies the coloring rendering capability of a given light source w.r.t., a reference light under the same correlated color temperature.
  - CRI is defined only for light sources that are approximate white, i.e., the chromaticity distance to the Planckian locus is below a threshold.

- The reference light is:
  - A blackbody (some form of incandescent light) when CCT is below 5000K.
  - A standard illuminant D (some form of daylight) when CCT is above 5000K.

Color Rendering Index

- Pick a set of standard samples with given spectral reflectance.
- For each standard sample, illuminate it with both the test light and the reference light. Calculate the two sets of XYZ chromaticities, apply von Kries chromatic adaption, and calculate the distance.
- Take some form of average across the samples and normalize to 100.

https://en.wikipedia.org/wiki/Color_rendering_index
Interpreting CRI

- Lights that are more similar to the reference lights (incandescent or daylight) have higher CRIs. Reference lights have a CRI of 100.
- Generally, lights with continuous spectrums have higher CRIs and lights with discrete spectrums have lower CRIs.
  ▶ A continuous spectrum better integrates across the entire visible range.

https://www.derunledlights.com/100-faq-about-led-strip-lights/
Display vs. Lighting

- We use a display because we want it to emit the right colors that our eyes will directly see.
  - Reproducing the chromaticity (using metamerism) is key. Spectrum is not important.
- We use a lighting system mostly to light an object so that we can see its color better.
  - CRI matters the most.
  - There are times we just need some light, too.


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Luminous Efficacy

\[ Y = 683 \frac{lm}{W} \int \Phi(\lambda)V(\lambda)d(\lambda) \]

\[ K = \frac{Y}{\int \Phi(\lambda)d(\lambda)} \]

- **Luminous efficacy**; unit is lumen/watt. K has a maximum possible value of 683 lm/W, for the case of monochromatic light at a wavelength of 555 nm.
Luminous Efficacy

K ≈ 15 (2% of max)  
CRI ≈ 100

K ≈ 70 (11% of max)  
CRI ≈ 80-90

Heating the tungsten filament.

https://www.thespruce.com/t-type-fluorescent-light-bulbs-1152396
Fluorescent Light

- **Phosphors**: fluorescent materials, which absorb photons and emit lower-energy (longer-wavelength) photons.
- Usually use ultraviolet light to light the phosphor coating inside a lamp.
- The UV light is generated by applying current to excite mercury vapor.
- Could mix different phosphors to improve CRI.

Display: Transforming Electrons to Photons

Emissive Displays (e.g., OLED)

Light-Filtering Displays (e.g., LCD/Projector)

Color Mechanism: Emissive Display

- Light generated at each pixel using light-emitting diodes (LED).
  - Semiconductor materials: electron -> photon.
  - Variants: OLED, QLED, AMOLED, etc.
  - Two common LEDs: AlGaNp and InGaN; different mixtures generate different spectrums.

Controlling Brightness in Emissive Display

- The higher is the current of the driver circuit and the lower is the temperature, the higher is the light output brightness (lumen).

https://www.researchgate.net/figure/Luminous-flux-output-of-a-typical-commercial-white-LED_fig3_318431510
Producing White in Emissive Display

- The actual reference white depends on the display spec (e.g., D65 in sRGB).
- Could use more than 3 primaries.
- Trade-off:
  - More primaries → more stable white (one primary being off a little doesn’t affect the “whiteness” much.
  - More primaries means more LEDs (form factor). The luminance efficacy (lumen/watt) might be lower depending on what LEDs are used.
- LEDs age at different rates; adjustment.

Human Factors in Lighting, 2014, Chapter 1.7.3.9
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› LEDs age at different rates; adjustment.
Color Mechanism: Light-Filtering Display

- White light source is **filtered** and attenuated at each pixel to control color and light intensity.
- Used in Liquid Crystal Displays (LCD) and DLP projectors.

My monitor LG 27UK850-W (LCD)
Controlling Brightness in LCD

- White light source is attenuated by liquid crystal within each pixel to control light intensity.


https://www.amazon.com/Casio-Digital-Watch-Black-F-91WG-9QEF/dp/B07QK38Q9K
Controlling Brightness in LCD

- White light source is attenuated by liquid crystal within each pixel to control light intensity.

Liquid crystal orientation depends on the applied voltage. The orientation induces rotation of the polarization of light.

Orthogonal. Blocking lights without the liquid crystal.
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Orthogonal. Blocking lights without the liquid crystal.

🤔 Characters on LCD watch fade away when battery is low. Why?


“Producing” Color in LCD

- White light source + color filter array at each pixel to generate color.
  - Could have different filtering array patterns.
  - Lower efficiency due to filtering.

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Pointillism and Color Filtering Patterns

Seurat, Parade de cirque, 1889

Paul Signac, Femmes au Puits, 1892

Filters in a pixel

https://www.semanticscholar.org/paper/A-Modified-Stripe-RGBW-TFT-LCD-with-Engine-for-Lai-Tsai/dec5b8d33c4958e76d0ce46a1262891578311f5f709b0e0d
https://en.wikipedia.org/wiki/Pointillism
Producing White Backlight in LCD

Combining RGB LEDs.

Using a white LED, which works by using a blue LED to light phosphor, which generates the rest of the spectrum for a white light. Also called the “phosphor-converted white LED”. Similar to fluorescent lamp.

https://en.wikipedia.org/wiki/Light-emitting_diode
https://www.display specifications.com/en/model/F0f1f0a4
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Blue LED (InGaN, peaks at 465 nm)

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Spectrum emitted from YAG yellow phosphor under the blue LED.

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Combining RGB LEDs.

From my LG LCD monitor

Blue LED (InGaN, peaks at 465 nm)

Spectrum emitted from YAG yellow phosphor under the blue LED.
Producing White Backlight in LCD

๏ **Spiky/narrow spectrum** → better luminous efficacy but worse color rendering capability (lower CRI).

๏ **The three LEDs might not age at the same speed** → needs adjustment.

๏ **LED emissions might change with angle** → white will change with viewing angle.

๏ **Wide spectrum** → **lower** luminous efficacy but better color rendering capability (higher CRI).

https://en.wikipedia.org/wiki/Light-emitting_diode
Field Sequential Color (FSC)

- Flash each primary at a high rate. Relies on the human vision system to fuse the successive images into a color picture.
- Color filtering array **spatially** adds colors; FSC **temporally** adds color.
- Compared to using color filtering arrays:
  - + 3X higher resolution if nothing else changes.
  - + higher luminous efficacy (if not using filtering).
  - + manufacturing cost is lower.
CBS FSC TV System

- CBS debuted the FSC TV system in 1940.
  - Obsolete now.
  - Watch a video demonstration here!
- 24 rotations per second. Each color is scanned twice per rotation.
- Transmitted images are black and white. Each image (also called a field) is unique and is in-sync with the color filter.
  - Each B/W pixel encoded brightness.
- $24 \times 6 = 144$ fields/s transmitted.

https://labguysworld.com/Goldmark1_001.htm
FSC in Digital Light Processing (DLP) Projectors
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The spinning color wheel (only 1 in the projector) controls the color of each pixel.
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FSC in Digital Light Processing (DLP) Projectors

Per-pixel mirror controls the brightness of light at each pixel. “Off” means the mirror reflects light away from the lens. A mirror can be switch between on/off thousands of times a second and with ~1024 levels (resolution).

The spinning color wheel (only 1 in the projector) controls the color of each pixel.
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FSC in Digital Light Processing (DLP) Projectors

1998 InFocus LP425z

Lens (projects lights)

Color wheel

DMD

Color Breakup in FSC

- Imperfect overlap of the three subfields on the retina caused by a relative velocity between displayed objects and an observer’s eyes, e.g., saccadic eye movements or smooth pursuits of moving objects.

Three-Chip Projectors

https://www.projectorpoint.co.uk/projectorlcdvsdlp
https://hometovs.com/should-you-buy-a-lcd-dlp-or-lcos-projector/
Dynamic Range

- Dynamic range/contrast: luminance ratio between white and black.
  - Natural scenes: ~20 stops (measurement)
  - Typical Display: ~10 stops (LG 27UK850); of course every display you buy touts HDR…
  - HDR Display: 14.2 stops (UHD Alliance Certified HDR LCD display)
  - Paper: 6-8 stops (typical value); related to pigment density

- Note that the contrast from vendor specification might be for the ratio between the brightness white and the darkest black.
Review: Tone Mapping

Scene → Camera → Display → Print → Eyes

Rendering the Print: the Art of Photography
Dynamic range doesn’t tell the **absolute** luminance, i.e., brightness, which is measured in cd/m² or “nits”.

- **My monitor LG 27UK850-W (LCD):** 350 cd/m²
- **iPhone 12 (OLED):** typical 625 cd/m² (1200 cd/m² max)
- **Pixel 5 (OLED):** 699 cd/m²

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https://www.displayspecifications.com/en/model/c6f10ad
https://www.gsmarena.com/google_pixel_5-review-2185p1.php
Display Color Space

Display's native color space usually doesn’t (and probably shouldn’t) match precisely any standard color space. It depends on the (LED) primaries actually used in the display.

- **sRGB**
  - sRGB is a color space, developed jointly by Hewlett-Packard and Microsoft in 1996. It is used in different devices such as printers, displays, TV sets, cameras, etc. The sRGB color space covers about 72% of the NTSC color space.
  - \( \approx 99 \% \) (percent)

- **Adobe RGB (1998)**
  - Adobe RGB (1998) is a color space, developed by Adobe Systems in 1998. It has a wider gamut than the sRGB (mainly in the cyan-green range of colors) and is widely used in professional printing.
  - \( \approx 73 \% \) (percent)

- **DCI P3**
  - DCI P3 is a color space, introduced in 2007 by the SMPTE. It is used in digital cinema and has a much wider gamut than the sRGB.
  - \( \approx 75 \% \) (percent)
Display Color Space

Measured spectrums of the display displaying images of sRGB R, G, and B primaries.

Modeling spectrums of the primaries of standard color space as a Gaussian.

DCI P3
DCI P3 is a color space, introduced in 2007 by the SMPTE. It is used in digital cinema and has a much wider gamut than the sRGB.

≈ 98.5 % (percent)
Which Standard Color Space Does a Display Use?

- A color profile (standardized by ICC) specifies what color space the display is to use. A system can switch between many profiles.
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![Diagram showing default profiles made for the two displays](image)

Other profiles that are available in the system; you can choose which one to use.
Which Standard Color Space Does a Display Use?

macOS’s ColorSync Utility tool

The color gamut of P3 in XYZ space. The gamut is a 3D concept!
Which Standard Color Space Does a Display Use?

The XYZ chromaticity of the primaries in the P3 color space. The chromaticities are chromatically adapted to D50 as required by ICC. The ‘ndin’ tag is for unadapted chromaticities of the primaries.

The color gamut of P3 in XYZ space. The gamut is a 3D concept!
Display Oriented Power Optimizations

Slowly decreasing the display brightness during long active screen intervals.

Use an ultrasonic-based approach to detect the user-screen distance, and reduce display resolution when the distance increases.
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Slowly decreasing the display brightness during long active screen intervals.

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How about AR/VR displays? What sort of characteristics in human perception can we leverage to optimize AR/VR displays?
Reference Materials

- **LEDs**:
  - [http://maltiel-consulting.com/Light_Emitting_Diode-LED_semiconductor_maltiel.htm](http://maltiel-consulting.com/Light_Emitting_Diode-LED_semiconductor_maltiel.htm)
  - Non-laser Light Sources: High-luminance LEDs target emerging automotive lighting applications, 2018
- **Sequential color systems**:
  - CBS FSC TV system ([Video](#))
  - Modern reproduction ([this](#) and [that](#))
Reference Materials

- FSC color breakup:
  - A Review of Color Breakup Assessment for Field Sequential Color Display, 2019
  - Suppressing color breakup in LCDs, 2008
  - Color breakup visibility thresholds for 2-field sequential colors, 2017

- Brightness comparison between smartphones from gsmarena.

- Measured color space of displays by clarkvision.

- A “short” description of ICC profile.

- Visual illustration of rendering intent by Cambridge in Color.