Color
• Physical Color

• Digital Color

• Color Manipulation
What Is Color

• Color can also be thought of an object’s **visual response** to light
  • A green plant without light will be black
  • A green plant with light will absorb some energy for photosynthesis, and then emit some green light
    • This emission is its visual response

• Color gives us a language for communicating similar energies that our eyes pick up
  • **Example:** picking colors for a house

A Lowe’s, Probably.
What Is Light

- Light is electromagnetic radiation
  - Generated as an oscillation in the electromagnetic field
  - Is light a wave, or a particle?
    - Yes.

- The frequency of oscillation determines the color of light
  - Most light is not visible!
  - Frequencies visible are a part of the visible spectrum

- White is the combination of all visible frequencies
- Black is the absence of all visible frequencies

- Color is a range of frequencies
  - Scientifically referred to as a spectrum
Light Spectrums

- **Emission spectrum** describes range of light frequencies emitted from a light source
  - Combination of frequencies gives the overall light color
  - Integrating over the spectrum gives the energy output
  - Higher energy output = more energy required to power
    - **Example:** light bulb
  - Measured as intensity per frequency

- **Absorption spectrum** describes range of light frequencies absorbed from a light source
  - Frequencies not absorbed are reflected back
  - Measured as percent absorbed per frequency
Emission Spectrum Examples

- **Daylight**: Sun-like
- **Incandescent**: Energy efficient
- **Fluorescent**
- **Halogen**
- **Cool White LED**
- **Warm White LED**
Absorption Spectrum Examples

plants are green because they do not absorb green light
Absorbed Light

- Converted to heat
  - Wearing dark clothes makes you warmer

- Converted to fuel biological ecosystem
  - Photosynthesis requires energy to move around electrons

- Converted to electrical energy
  - Solar panels are black to absorb as much visible light

(This thing absorbs everything)
(he absorbed my pizza rolls once)
So What Is Color

- Color is emission multiplied by the reflectance
  - Reflectance is whatever percentage is not absorbed

- The sun’s emission is near-equal parts of all visible light
  - Reason why everything is its ‘true’ color under sunlight

Emission Spectrum $E(v)$

Reflectance Spectrum $R(v)$

Result Reflected $ER(v)$
Color By Emission

- We can change the color of objects by changing the emitted light
  - Plants under red light will appear red, etc.

- Red and blue plants appear much darker
  - Most light absorbed for photosynthesis

- Can also use non-visible light (UV) to show colors not originally there
‘Eye’ See What You Mean

- Eyes are biological cameras
  - Light passes through the pupil [black dot in the eye]
  - Iris controls how much light enters eye [colored ring around pupil]
    - Eyes are sensitive to too much light
    - Iris protects the eyes
  - Lens behind the eye converges light rays to back of the eye
    - Ciliary muscles around the lens allow the lens to be bent to change focus on nearby/far objects

- 130+ million retina cells at the back of the eye
  - Cells pick up light and convert it to electrical signal
  - Electric signal passes through optic nerve to reach the brain

Image appears backwards!
Don’t worry, brain flips it right-side up
The Biological Camera

- **Pupil** is the **camera opening**
  - Allows light through

- **Iris** is the **aperture ring**
  - Controls aperture

- **Lens** is the...well, **lens**
  - Can change focus

- **Retina** is the **sensor**
  - Converts light into electrical signal

- **Brain** is the **CPU**
  - Performs additional compute to correct raw image signal
Rods & Cones

- Cones are primary receptors near fovea used under high-light viewing conditions
  - Approx. 6-7 million cones in the human eye
  - Capture color
- Rods are primary receptors far from fovea used under low-light viewing conditions
  - Approx. 120 million rods in human eye
  - Capture intensity

Best vision at center of cones!

Human blind spot
A Little Trick

- Close left eye
- Stare at the circle
- Move closer to the screen
- Move farther from the screen
- Continue until the plus sign disappears

- Close right eye
- Stare at the plus
- Move closer to the screen
- Move farther from the screen
- Continue until the plus sign disappears

Works best on a laptop/device close to you!**

**https://www.webmd.com/eye-health/what-to-know-blind-spots-scotoma
Another Little Trick

• Grab someone and try it at home!
  • Have them hold up colored markers in peripheral [side] vision, bringing closer to center
  • Once you see a marker, guess the color
    • As the marker comes closer to center, did you get the color right?
Spectral Response of Cones

- Long, Medium, and Small cones pick up Long, Medium, and Small wavelengths respectively.
- Each cone picks up a range of colors given by their response functions.
  - Not much different than absorption spectrum.
- Each cone integrates the emission & response to produce a single signal to transmit to the brain.
  \[
  S = \int_{\lambda} \Phi(\lambda) S(\lambda) d\lambda \\
  M = \int_{\lambda} \Phi(\lambda) M(\lambda) d\lambda \\
  L = \int_{\lambda} \Phi(\lambda) L(\lambda) d\lambda 
  \]
- Uneven distribution of cone types in eye.
  - ~64% L cones, ~32% M cones ~4% S cones.
The Biological Camera [Again]

- Eyes perceive green color better than any other color
  - Thought to be an evolutionary property of humans
  - Sun emits more green light, our eyes adapt to capture more green light

- Camera sensor has 2x as many green sensors as blue or red
• **Mantis Shrimp** are a larger breed of shrimp that live in tropical waters
  • Known to have the most complex eyes of any creature studied on Earth

• Humans have 3 different cone receptors (SML)
  • These guys have 12
  • Can also detect UV and polarized light

• Does this mean shrimp see better than us?
  • Cognitive ability of a shrimp is much less than humans, leading shrimp to have a hard time distinguishing between colors

• **Lesson:** to have good eyes, you need a good brain
Metamers

• Different spectrums can be integrated over the SML activations to produce the same SML colors
  • Yellow can be made from yellow wavelengths
  • Yellow can also be made from equal parts red and green wavelengths

• Important for color reproduction!
  • No need to capture the entire spectral distribution, just the end SML values are enough
    • Led the way for digital color spaces

• Problem: trying to represent colors in print
  • Digital colors (pixels) have full control of emission
  • Physical colors (prints) only have control of absorption
    • Changing the emission (lighting) will change the resulting image colors
• Physical Color

• Digital Color

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Color Models

- Things to consider when picking a color:
  - **Gamut**
    - The area of color that is covered
  - **Conversion**
    - Converting from digital to print
  - **Convenience**
    - Easy for users to pick the color they want
  - **Storage**
    - Low data overhead

- **Additive color** starts with black and add colors
  - **Ex:** a black display emits no light, turning on RGB pixels adds a blending of emissions to create colors in regions
  - **Common:** RGB

- **Subtractive color** starts with white and remove colors
  - **Ex:** a white paper reflects all light, printing on a paper removes reflectance of certain colors in printed areas
  - **Common:** CMYK
Let’s Shed Some Light Here
Types of Color Models

- **RGB [ Red Green Blue ]**
  - Ubiquitous RGB displays

- **CMYK [ Cyan Magenta Yellow Key ]**
  - Common for printing

- **HSV [ Hue Saturation Value ]**
  - Most intuitive

- **SML [ Small Medium Large ]**
  - Weighted average of cone response spectrums

- **XYZ [ 3D color space ]**
  - Absolute color space
Absolute Color Spaces

- An **absolute color space** will always present the same color given the same coordinates
  - RGB is not an absolute color space
  - XYZ is an absolute color space
    - CIEE XY space drops Z (luminance)
- **Idea:** define RGB color space as 3 vertices on the CIEE XY color space
  \[
  R = 0.65x + 0.31y \\
  B = 0.15x + 0.05y \\
  G = 0.31x + 0.57y
  \]
- Any color within the triangle can be produced with an RGB display
- Can share common RGB spaces for consistency:
  - REC.709
  - DCI-P3
  - REC.2020
Absolute Color Spaces

Producing high-range RGB color displays aren’t cheap.
MacAdam Ellipses

- Any color sampled from an ellipse is the same as the color in the center to the human eye
  - Not a transitive property: two colors on the extreme will look different

- **Chromaticity** is a color absent of any luminance
  - Radius of ellipse in a given direction measures the lack of chromaticity difference in changing a given color by a given amount to the human eye
Nonstandard Color Vision

- Morphological differences in eye can cause people & animals to see different ranges of color
  - 2 cones instead of 3
  - Different response functions per cone
  - Different cone sensitivity
  - More or less cones

- Alternative chromaticity diagrams help visualize color gamut, useful for designing, e.g., widely-accessible interfaces

- **Important for color theory:** pick colors that are universally (or as universally) recognizable as possible
Encoding Color Values

- RGB colors commonly encoded as 8-bits per channel
  - 256 possible values
  - If including alpha, add another 8 bits
    - Displays can now handle 16/24/32 bit channels
    - Continue to use 8-bits for backwards compatibility

- Hex format: #1B1F8A
  - 2 hex digits = 8 bits
  - Common in web development

- Uint8 format: (27, 31, 138)
  - Range of 0 - 255
  - Maps to displays easily

- Float format: (0.106, 0.082, 0.541)
  - Range of 0.0 – 1.0
  - Better precision with operation
  - Requires conversion to Uint8 at the end
Compressing Colors

- **Y’CbCr** color scheme common for modern digital video
  - **Y’** = luma: perceived luminance
  - **Cb** = blue-yellow deviation from gray
  - **Cr** = red-cyan deviation from gray

- Great compression properties!
  - **Y’** channel holds high frequency data
  - **Cb, Cr** channels hold low frequency data
Compressing Colors

Human vision much more sensitive to luminance than color!

[ original ]  [ full res Y' ]  [ low res CbCr ]  [ composite ]

Downsampled by a factor of 20 in each dim.
400x less samples
• Physical Color

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Color Conversion

• Convert color from one model (RGB) to another (CMYK)
  • In a perfect world, want to match output spectrum
  • Even matching perception of color would be terrific (metamers)

• In reality, information will be lost
  • Depends on the gamut of the output device

• Lots of standards & software
  • ICC Profiles
  • Adobe Color Management
Color Conversion

- Difficulty converting between colors
  - RGB -> RGBA
    - Fill alpha value with 1.0
  - RGBA -> RGB
    - Pre-multiply alpha value
    - Drop alpha value altogether
- Grey -> RGB
  - Copy grey value to each channel
- Grey -> RGBA
  - Convert Grey -> RGB then RGB -> RGBA
- RGB -> Grey
  - Take the average of each channel
  - Take a weighted average based on human perception
- RGBA -> Grey
  - Convert RGBA -> RGB then RGB -> Grey
Brightness & Contrast

• Consider a color mapping from the range [0.0, 1.0]:
  \[ y = x \]

• Brightness brings colors closer to white or black
  \[ y = x + b \]

• Contrast brings colors closer to the average grey color
  \[ y = c \times (x - 0.5) + 0.5 \]

• They can be combined as a 2-for-1 deal
  • Commonly found as a single effect in most color-grading software:
    \[ y = c \times (x - 0.5) + 0.5 + b \]

• Values must be clamped back to range [0.0, 1.0]!
Saturation

- Saturation moves colors closer or farther from their ‘max’ value
- Compute the greyscale value of a color using the weighted greyscale average:
  \[ x_{grey} = 0.299 \times r + 0.587 \times g + 0.114 \times b \]
- Linearly interpolate the original color with the grey color:
  \[ y = a \times x + (1 - a) \times x_{grey} \]
- If \( a > 1 \) then the output image becomes oversaturated
- If \( a < 0 \) then the output image becomes undersaturated

\[ 2 \times \text{brown} - 1 \times \text{grey} = \text{brown} \]

artifacts of jpeg compression!
Gamma Correction

- When we look at an object, using two lights does not make it twice as bright [non-linear]
  - When a camera captures an object, using two lights emits two times the amount of photos, and the sensor picks up twice as many photons, making the observation twice as bright [linear]

- Cameras have a tendency to map colors too brightly, while having a hard time capturing darkness
  - Gamma correction modifies the signal by some $\gamma$:
    \[ y = x^{-\gamma} \]
  - Then, when displaying the image, un-modifies the gamma:
    \[ y = x^{\gamma} \]
Why Bother With Gamma Correction?

- Luminance is discretized into 8-bits from [0, 255]
  - Cameras pick up a lot of bright light
    - Small changes in darkness will not be captured by the sensor
    - Leads to ‘dark bands’
  - Idea: if a majority of the data is on the brighter end, let’s encode luminance as a logarithmic curve rather than a linear curve
    - Small changes in darkness can now be captured
  - Apply inverse of gamma correction for displays
    - Display emits light, eyes will autocorrect for it in a non-linear fashion the same as with real life
  - Main idea: cameras should save data non-linearly the same way eyes see the data

<table>
<thead>
<tr>
<th>Linear TRC</th>
<th>sRGB TRC</th>
<th>LAB L* TRC</th>
<th>Rec709 TRC</th>
<th>Gamma 1.8 TRC</th>
<th>Gamma 2.2TRC</th>
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<tbody>
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<td><img src="image2.png" alt="With Gamma Correction" /></td>
<td></td>
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</tr>
</tbody>
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How do we use color in computer graphics?
Graphic Design

• Colors convey different emotions
  • Pick the right set of colors to convey the right emotions
• Find relationships between colors
  • Known as color theory
Color Theory

- Color theory combines several physical and cognitive abilities of humans to produce ‘appealing’ colors
  - Human optical ability
  - Psychological responses
  - Culture

- Goal is to make designs with physically recognizable colors that also invoke some targeted emotional response
  - Ex: Food colors invoke hunger