Light

- No light $\Rightarrow$ nothing is visible

- With a light source, what do we see?
  - Light *transmitted* directly from the source into the eye, or
  - Light *reflected* off objects in the scene
Physics of light

- Light is a form of **electromagnetic radiation**
- Travels as waves at the speed of light
- Characterized by energy/power contributions at different **wavelengths** ($\lambda$) or **frequencies** ($f$) — spectral power distribution (SPD)

  - Recall: $f\lambda = \text{speed of light} \ c = 3 \times 10^8 \ \text{m/s in vacuum}$
  - Light travel “slows down” in media, e.g., water
Physics of light

- The color of a light is determined by the energy it emits at various wavelengths (frequencies)

- Visible lights have wavelengths in the range of 350 – 780 nanometers (1 nm = 10^{-9} m) — visible spectrum
The visible spectrum

Visible light

Log scale

Frequency (Hz)
wavelength (nm)

10^15 10^13 10^11 10^9 10^7 10^5 10^3 10^1 10^{-1} 10^{-3}

am radio fm radio TV microwave infrared ultraviolet x-rays gamma rays

Two color spectra (SPDs)

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Color

Why do we see colors?

- Light source has color — determined by SPD
- When colored light reaches a colored object, pigments in the object surface absorb certain colors (light) and reflect the rest
- A pigment is any substance that absorbs light
Example: photosynthesis

\[ 6\text{H}_2\text{O} + 6\text{CO}_2 \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \]

- Why are leaves green?
  - Plants, leaves, and other photosynthetic organisms have **Chlorophyll** [klaWR-uh-fil]
  - Chlorophyll: a (green) pigment that absorbs all wavelengths of visible light except green, which it reflects and can be detected by our eyes.
Light in OpenGL

- Assume that light travels in a straight line

- Light is emitted …
  - at a fixed rate (no “burn-out”) and equally in all directions
  - intensity may decay with respect to distance
Light in OpenGL

- Light sources and material reflectance have 3 components: *ambient*, *specular*, *diffuse*

- Ignore precise frequency composition of colored light and care about its component-wise intensity (energy) – R, G, B

- Several types of light can be modeled in OpenGL, e.g., *ambient light*, *point light*, *directional* or *distant* (set w = 0) lights and *spot lights*
Human visual system

- Light sensors on the retina: **rods and cones**
- The rods
  - Look like rods
  - Enable us to see “in the dark”
  - Function well in dim light and are “blind” to colors
  - Night vision …
Cones: color perception

- Cone cells are responsible for the perception of colors
  - Look like cones and function in bright light
  - Rods outnumber cones 10:1 except at the fovea — the most valuable square millimeter of tissue in the body, where there is high concentration of cones
  - **Tristimulus via 3 types of cones**: optimally sensitive to 430 nm (B), 530nm (G), and 560 nm (R), respectively
  - They collectively trigger a sensation in our brain
  - We often approximate color using **3 primaries**, e.g., R, G, B → **color space is 3-dimensional**
The dog visual system

- What do dogs see?
- Dogs can only see B/W?
  - Mistake! They do see color!
- Dogs have two types cone cells
  - Recognize short and medium-to-long wavelengths of light, corresponding to bluish hues and red-yellow
  - See almost identical as a red-green colorblind human
- Homework: How could you find this out? 😊
(Additive) Color matching

- How to find the RGB composition for the various colors?
  - Visual color matching = finding right mix of R, G, B
  - Metamers — reality vs. perception: colors with different spectra but are perceptually identical, as long as the combined effects on color receptors (cones) are the same
The RGB model

Problem 1: Not all visible colors are reproducible by adding RGB – some color needs to have R added to it to get a match

Problem 2: The RGB model is not “intuitive” – it is not often the way we perceive or describe colors
Intuitive color description (HSV)

- **Hue**: what color is it, red, blue, purple?
  - Basically determined by dominant wavelength in the spectrum

- **Saturation** (excitation purity): how vibrant or pastel/washed out?
  - how far the color is from a gray of equal intensity, e.g., red is more saturated than pink

- **Lightness** (luminance or value): intensity of light — basically the integral of $P(\lambda)$
Represent all colors: CIE XYZ colors

- CIE ("Commission Internationale d’Eclairage") uses another set of primaries: X, Y, Z
- **Positive weights** only can match all visible colors

CIE color matching functions

The CIE color space and the RGB cube inside
3D to 2D: CIE chromaticity diagram

- 3D color space hard to manipulate and visualize
- Project to 2D: Defined by normalizing against $X+Y+Z$ (the total light or luminous energy)
  - Project CIE color space onto plane $X + Y + Z = 1$:
    \[ x = \frac{X}{X + Y + Z}, \]
    \[ y = \frac{Y}{X + Y + Z}, \]
    \[ z = 1 - x - y \]
- Then project onto the xy-plane to get the 2D chromaticity diagram
- Chromaticity values depend on hue and saturation only
Reading the chromaticity diagram

- Curved boundary: spectrally pure (100% saturated) color \( \lambda \)

- Lower part: nonspectral colors (without dominant wavelength), e.g., purple

- Standard illuminant C
  - white sun light measured in some standard way
  - it is near the point \( x = y = z = 1/3 \).
Use of the chromaticity diagram

- When two colors are mixed together, the new color lies along the straight line between the original colors
  - e.g. A is mixture of B (spectrally pure) and C (standard white light)
  - B: dominant wavelength of A
  - AC/BC is the excitation purity or saturation of A
  - Complementary colors: sum add to C, e.g., D and E
Dominant wavelength & nonspectral color

- **Dominant wavelength**: spectral color that can be mixed with white light to produce the desired color.

- **F** is a mixture of **C** and **G**, but **G** is not spectral.

- **F** is non-spectral and has no dominant wavelength.

- Its dominant wavelength is set to be the complement of **B**, denoted by 555 nm.
Color gamuts

- **Color gamut**: space of colors that a physical device can represent, e.g., color gamut from mixing $I$, $J$, $K$ is the triangle shown.

- No triangle can lie within the horseshoe and cover all.

- So no additive color model with **visible colors as primaries** can produce all visible colors.
Color conversion

- Conversion between XYZ and RGB? One example:

\[
\begin{pmatrix}
R \\
G \\
B
\end{pmatrix} = \begin{bmatrix}
1.730 & -0.482 & -0.261 \\
-0.814 & 1.652 & -0.023 \\
0.083 & -0.169 & 1.284
\end{bmatrix}\begin{pmatrix}
X \\
Y \\
Z
\end{pmatrix}
\]

- CIE color-matching functions are linear combinations of the RGB color-matching functions

- Conversion from other model to XYZ is via RGB
Color model we use: RGB

- Three primaries: R, G, and B
- Employs a Cartesian coordinate system
- RGB primaries are **additive**: individual primaries are added to give result
- Suitable in case of **transmitted light**
- Used in CRTs
Subtractive color model

- CMY (Cyan, Magenta, Yellow), the primaries
  - “secondary”: \( C = G + B, M = R + B, \) and \( Y = R + G \)
  - subtractive: C, M, & Y subtract colors from white
  - complements of RGB, \( C = 1 - R, M = 1 - G, \) \( Y = 1 - B \)
  - e.g., what is the color \((1, 1, 1)\) in the CMY model? – black

- Suitable in case of reflected lights
  - E.g., in color printing and film
  - Color seen is the color reflected from the printing media after absorption (or subtraction)
Subtractive color model

- Examples:
  - Cyan ink on paper under white light, we see …?
    Answer: $C = 1 - R = B + G$ — it absorbs or subtracts $R$ and reflect $B + G$ in white light, so we see cyan
  - Magenta light shining on yellow paper, we see …?
    Answer: $Y = 1 - B = R + G$ — it absorbs $B$ in Magenta $(R+B)$, so $R$ is reflected – we see red!
  - **Vibration frequencies** of atoms in the light wave and pigment material dictate which wavelengths absorbed
Other color models (aside)

- **YIQ:**
  - used in US commercial color TVs
  - Y: brightness
  - I & Q: Hue and saturation (chromaticity)

- **HSV (H: 0 – 360; S, V: 0 – 1)**
  - based on intuitive appeal of the artists
  - employs a **cylindrical coordinate** system
  - its color space is a hex cone, see [F]

- Can convert between all these models

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Achromatic color or light

- All about intensity (no hue or saturation factors)
  - Bi-level device (plotter or printer), can only display one of two intensities at any point – B/W
  - A black and white TV can produce many different intensities at any single point – gray scale
- Simplified case but still interesting
- Approaches can be extended to individual color component, e.g., R, G, or B
Some questions

- An illumination model can produce an intensity value anywhere in \([0, 1]\).

- But any display device can only provide a finite number of intensity levels, say 256 (8 bit), which ones to use?

- How many intensities do we need to represent an image in a \textit{continuous-tone} manner? – so that our eyes cannot see discontinuities due to lack of intensity levels.

- What good can we do to bi-level (B/W) displays?
Which intensities to choose?

- Goal: distribute limited number of intensities within $[0, 1]$ so that transitions between levels are constant

- Evenly space intensity values? – Not a good idea
  - What matters is perceived lightness or brightness
  - Similar to sound perception, our perception of light and color intensities is sensitive to ratios, not absolute values, e.g., from intensities 2 to 4 then to 6, we notice a much bigger jump from 2 to 4; $2$-to-$4 \approx 4$-to-$8$

- So intensity values should be spaced logarithmically, e.g., $1/32, 1/16, 1/8, \frac{1}{4}, \frac{1}{2}, 1$
How many intensities? (exercise)

- Enough means the number of intensities is sufficient to reproduce a continuous-tone image

Let $r$ be ratio between adjacent intensities

The eye cannot distinguish them if $r \leq 1.01$.

Let $l_0$ and 1 be minimum and maximum intensities, and $n$ the required number of intensities, we want

$$r = 1.01 = (1/l_0)^{1/(n-1)}, \text{ since } l_0 \cdot r^{n-1} = 1$$

Finally, $n \geq \log_{1.01}(1/l_0) + 1$. Note that $l_0 > 0$ and is typically in the range $[.005, .025]$
Digital halftoning or dithering

- What if displayable intensities not enough? — $n$ is too big
  - Take advantage of our eyes’ **spatial integration**: if a small area is far enough, we see the overall intensity of the area
  - Raster displays: reduce spatial resolution and increase number of intensities – **digital halftoning** or **dithering**
Digital halftoning or dithering

- Example: approximate 5 intensity levels with B/W using the following $2 \times 2$ dither patterns, see [F] for more details

- B/W printing (e.g., newspaper): use black dots of varying sizes