CSE 252A: Color

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1 Color

There are multiple ways we can describe color. We can describe it in terms of *wavelength* (a positive function ranging from 400 to 700 nm, with infinite granularity), *names* (e.g. harvest gold, vermilion, ebony...), *RGB values...*

The spectra that make it to our eyes are functions of both the spectra of illumination $I(\lambda)$ (properties of lights) and the spectra of reflectance $R(\lambda)$ (properties of materials). The spectra are continuous functions of the energy at each wavelength. Put together, the color signal $C(\lambda)$ is

$$C(\lambda) = I(\lambda) \ .\!* \ R(\lambda)$$

where `.*` denotes a pointwise multiplication.

In addition to $I(\lambda)$ and $R(\lambda)$, measured color depends on retinal response functions (sensitivities). *One takeaway is that colors aren't intrinsic properties of objects; they depend on external factors like lighting as well. A shirt might only be auburn under certain lighting conditions.*

Trichromacy Consider the problem of color matching, where we want users to adjust the levels of multiple (e.g. three primary) colors in order to match a given spectrum. If we allow subtractive color matching (enable the use of "negative" amounts of the adjusted colors by adding them to the to-be-matched spectrum), most people are able to successfully perform the task (in the same way).

Color-blind people create what they think is a match[1] with only two colors. This is because they're matching according to their visual system, with might involve a sensor response with two kinds of color receptors.

The fact that almost everybody requires only three colors for matching (e.g. we don't get anything else out of having four colors) indicates that there are only three different color receptors in the eye.

Humans have three types of cones (S/blue, M/green, L/red). The response of cone k with sensitivity curve $\rho_k(\lambda)$ to physical energy $E(\lambda)$ is

$$\int \rho_k(\lambda) E(\lambda) d\lambda$$

Since we have three cones, we use three numbers to describe colors. We choose three primary colors $P_1(\lambda)$, $P_2(\lambda)$, and $P_3(\lambda)$. If we determine how much of each primary is needed to match

[1] Nobody really creates an exact physical match with only x colors, only the closest approximation in that basis which looks exact to us because that's all we can see. But a spectrometer would tell us there's a difference.

monochromatic colors λ (energy only at a single wavelength of light) for each value of λ, we will have defined color matching functions $p_1(\lambda)$, $p_2(\lambda)$, and $p_3(\lambda)$.

Note that when we do this, there will always be subtractive matching involved somehow (for some chroma, we'll need negative values of at least one of the primaries).[2]

There are many color spaces (both linear and nonlinear; "linear" being where colors are constructed as linear combinations of primaries), each of which uses three numbers to describe a color.

- In RGB, we always describe colors as $[0, 1]$ amounts of each of R, G, and B, meaning we can draw it as a cube. Other color spaces might not have the same range for each coefficient.
- HSV (hue/saturation/value) projects RGB onto a cone, by taking a plane orthogonal to the white RGB value $(1, 1, 1)$ and projecting colors onto the plane (creating a hexagon with vertices "green," "yellow," "red," "magenta," "blue," "cyan"). We also allow for variation of value along the height of a hexcone with our hexagon at the top. White is at the center of the hexagon at the top and black is at the origin of the hexcone (the point at the bottom).
  - HSV is the color space for color pickers (the wheel things).
- The CIE-XYZ color space can also be projected to a plane, creating a 2D region on the border of which we have the fully saturated colors (single wavelengths of light). The region represents all human-perceivable colors. Toward the center we have more combinations and can draw out the gamuts of different output devices.
  - *Color gamut*: set of colors one can achieve with a particular set of technologies.
  - As the region isn't triangular, we can't make every color (additively) from just three primaries. The number of primaries gives the number of vertices of the gamut in the region. The more primaries we have, the bigger of a gamut we can make.

Metamers We might have two different lights that have different spectra but look the same.

Takeaways Light lives in a spectrum, and you'd have to use an infinite number of values to describe it as a physical quantity. RGB is a sampling, a discretized version of what actually exists, but is able to encode for the most part what humans see because we see color through three sensors.

In summary, color is something perceived. It is a function of both a physical quantity and a response, where the physical quantity is EMR in the visible spectrum and the response for humans is determined by three types of cone cells. Perceptually, it depends on a lot of factors such as lighting, spatially local colors, and temporally local colors.

[2] Such is not the case in the CIE XYZ space (the matching functions are nonnegative everywhere), but the primaries themselves are "fictitious" and have negative amounts of some wavelengths.