Light & Color

OUTLINE:

Physics

Perception

Color Reproduction

Physics of Light and Color

It all comes from electromagnetic (EM) radiation.

The amplitude of radiation is a function of wavelength λ.

Frequency $\nu = 2\,\pi / \lambda$

EM spectrum:

radio, infrared, **visible**, ultraviolet, x-ray, gamma-ray

← *long wavelength* / *low frequency* — *short wavelength* / *high frequency* →

- Don't confuse EM ``spectrum'' with ``spectrum'' of signal in signal/image processing; they're usually conceptually distinct.
- Likewise, don't confuse spectral wavelength & frequency of EM spectrum with spatial wavelength & frequency in image processing.

Perception of Light and Color, 1

Light is EM radiation that is visible to the human eye.

Wavelength range of visible band: approx. 400-700 nanometers. We're most sensitive to greens & yellows; not very sens. to blue.

Humans have evolved to sense the dominant wavelengths emitted by the sun; space aliens have presumably evolved differently.

In low light, we perceive primarily with rods in the retina, which have broad spectral sensitivity ("at night, you can't see color"). Rods have relatively good spatial resolution in the periphery as well as fovea (center).

In bright light, rods are overloaded, we perceive primarily with the three sets of cones in the retina, which have narrower spectral sensitivity roughly corresponding to red, green, and blue wavelengths. Cones are concentrated mostly in the fovea, so we have low spatial resolution in periphery. Green cones most populous, then red, then blue, hence our poor blue spatial sensitivity.

Perception of Light and Color, 2

Some people are colorblind; they have one or more sets of defective or poorly wired cones.

Other animals have fewer or more sets of cones (1-7).

Facts from neurophysiology: signals cones are combined in higher levels of processing in the retina and in the brain by neurons whose receptive fields (point spread functions) seem to come in several types: spot detectors, edge detectors, and line detectors. And each comes at a range of scales, orientations, and color channels.

The eye can focus various depths by changing the shape of the lens.

The eye has a huge dynamic range: 10 orders of magnitude (facilitated by eyelids, pupil, cone/rod, and electro-chemical adaptive mechanisms).

The eye and brain are remarkably good at color adaptation: perceiving the "color" of objects under light sources of various colors and brightnesses. Perception is great at qualitative analysis, poor at quantitative analysis.

What is Color?

Color is human perception of light.

Our perception is imperfect; we don't see $P(\lambda)$, instead we see three scalars.

long wavelength (≈ red): $L = \int P(\lambda) s_L(\lambda) d\lambda$

middle wavelength (≈ yellow): $M = \int P(\lambda) s_M(\lambda) d\lambda$

short wavelength (≈ blue): $S = \int P(\lambda) s_S(\lambda) d\lambda$

where $s_L(\lambda)$, $s_M(\lambda)$, and $s_S(\lambda)$ are the sensitivity curves of our three sets of cones.

Color is three dimensional because any light we see is indistinguishable to our eyes from some mixture of three spectral (monochromatic, single-wavelength) **primaries**.

Two spectral distributions that appear the same to a human, even though their spectra may differ greatly, are called **metamers**.

Additive vs. Subtractive Color

When working with light, we use **additive primaries**; often (but not always) red, green, and blue, since light adds by the superposition property of electromagnetism.

When working with pigments (ink or paint on paper), we use "**subtractive primaries"**; often (but not always) yellow, magenta, and cyan (& black), since pigments filter out light. The process is better described as multiplicative, not subtractive.

With paint, artists say "yellow + blue = green", but what's happening physically is:

"(spectrum that looks yellow) * (spectrum that looks blue)
= (spectrum that looks green)"

The Reproduction of Color

In realistic image synthesis, graphic design, and other settings, we want WYSIWYG color: what you see on the screen is what you get in your output (paper, video, film, whatever).

But both during design (producer) and during display (consumer),

- Monitors differ in brightness, color, contrast.
- Printers, paper, inks, and video projectors differ.
- Photographic film and film processing differs.
- NTSC video sucks (discards too much chroma information).
- Working conditions have differing light levels.
- Displays and inks have limited gamut.

What do we do?

CALIBRATE!

Color Calibration

Two methods:

Device-independent calibration: Use sensing devices to objectively measure spectra of various test colors (black, white, red, etc.), and compute a color transform to match them. If receiver can calibrate too, then you can transmit device-independent colors this way without knowing receiver's characteristics.

End-to-end calibration: Ask user to interactively adjust a color transform to match a printed color, for example, with a monitor color. This method is more practical because it doesn't require sensing devices, but is more limited, since it's receiver-specific.

In addition to color balancing, you need gamma correction (correction for nonlinearities) too.

Color Spaces

Color can be described in various color spaces:

spectrum - allows non-visible radiation to be described, but usually impractical/unnecessary.

RGB - CRT-oriented color space

good for computer storage.

HSV - a more intuitive color space; good for user interfaces

H=hue -- the color wheel, the spectral colors

S=saturation (purity) -- how gray?

V=value (related to brightness, luminance) -- how bright?

a non-linear transform of RGB, since H is cyclic.

CIE XYZ - used by color scientists, a linear transform of RGB.

other color spaces, less commonly used...

For extremely realistic image synthesis, use of four or more samples of the spectrum may be necessary, but for most purposes, the three samples used by RGB color space is just fine.

Color Space Transforms

Convert from RGB to spectrum:

$P_{RGB}(\lambda) = R\ P_R(\lambda) + G\ P_G(\lambda) + B\ P_B(\lambda)$

where $P_R(\lambda)$, $P_G(\lambda)$, $P_B(\lambda)$ are spectra of RGB phosphors

Convert from spectrum to RGB:

want spectrum and RGB that look the same (have same L,M,S):

L,M,S of $P(\lambda)$ = L,M,S of $P_{RGB}(\lambda)$

3 equations in 3 unknowns, with constant coefficients

two step process: find L,M,S from $P(\lambda)$, then do linear color transform with 3x3 matrix to convert to R,G,B

Transforms between RGB and CIE very similar; also expressed using 3x3 matrices.