Introduction to Color
Framing the Context

- Graphics used to concentrate on interaction, then “photorealism”, which was based on performance-centered hacks
- Now both are important, as is non-photorealistic rendering
- Photorealistic rendering increasingly physically-based and perception-based
- An understanding of the human visual and proprioceptive systems are essential to creating realistic user experiences
All You Need to Know About Color in CS123
Lecture Roadmap

- Motivation
- Achromatic light
- Chromatic color
- Color models for raster graphics
- Reproducing color
- Using color in computer graphics
Why Study Color in Computer Graphics?

- Physics and measurement for realism
  - what does coding an RGB triple mean?
- Perception and aesthetics for selecting appropriate user interface colors
  - why a bright red and orange striped bedroom is a bad idea
  - how to put on matching pants and shirt in the morning
  - what are perceptual/physical forces driving one’s “taste” in color?
- Color models for providing users with easy color selection
  - systems for naming and describing colors
- Color models, measurement and color gamuts for converting colors between media
  - why colors on your screen may not be printable, and vice-versa
  - managing color in systems with computers, monitors, scanners, and printers
- We study it as useful background for rendering and because it provides a good introduction to signal processing
  - also used for image processing and physically-based rendering
- Graphics group has worked on color tools for Adobe
Why is Color Difficult?

- Color is an immensely complex subject, drawing on physics, physiology, psychology, art, and graphic design.
- Many theories, measurement techniques, and standards for colors, yet no one theory of human color perception is universally accepted.
- Color of object depends not only on object itself but also on light source illuminating it, on color of surrounding area, and on human visual system (the eye/brain mechanism).

- Some objects reflect light (wall, desk, paper), while others also transmit light (cellophane, glass):
  - surface that reflects only pure blue light illuminated with pure red light appears black
  - pure green light viewed through glass that transmits only pure red also appears black
What is color?

• Color is a property of objects that our minds create – an interpretation of the world around us
  – unique to humans and higher primates

• Color perception stems from two main components:
  1) Physical properties of the world around us
     – electromagnetic waves interact with materials in the world and eventually reach your eyes
     – visible light comprises the portion of the electromagnetic spectrum that our eyes can detect (380nm/violet – 740nm/red)
     – photoreceptors in the eye convert light (photons) into electro-chemical signals which are then processed by our brains – rods and cones
  2) Physiological interpretation of “raw data” coming into our eyes
     – less well-understood and incredibly complex higher level processing
     – very dependent on past experience and object associations

• Both are important to understanding our sensation of color
Our Visual System Constructs our Reality: The Ultimate VR System

- **Still incompletely understood**
  - Understanding our “wiring” is insufficient
  - Both retina and brain work together to result in “seeing,” having a retina alone is insufficient
  - New tools (e.g. fMRI) greatly increases our understanding but also introduces new questions

- **Some viewing capabilities hardwired, others learned**
  - We acquire a visual vocabulary
  - What looked real a few years ago, no longer does

- **Huge innate pattern recognition ability**

- **Visual faster than higher-level cognitive processing**
  - For example roads use symbols instead of words for signs (but “dual coding” is always better)

- **Invariances/perceptual constancies are crucial for sense-making**
  - Size, rotation and position constancy of objects despite varying projections on the eye
  - Color constancy despite changing wavelength distributions
  - Person recognition despite everything else changing

- **Optical illusions**
  - Completing incomplete feature
  - Seeing patterns
  - Seeing 3d (perspective, camera obscura, sidewalk art)
  - But also artifacts: misjudgments, vection = apparent motion,…
Achromatic Light (1/2)

- Achromatic light: intensity (quantity of light) only
  - called intensity or luminance or measure of light’s energy or brightness
    - the psychophysical sense of perceived intensity
  - gray levels (e.g., from 0.0 to 1.0)
    - we can distinguish approximately 128 gray levels
  - seen on black and white displays
  - note Mach banding/edge enhancement – stay tuned
Achromatic Light (2/2)

- Eye is much more sensitive to slight changes in luminance (intensity) of light than slight changes in color (hue)
  - "Colors are only symbols. Reality is to be found in luminance alone... When I run out of blue, I use red." (Pablo Picasso)

- Picasso's Poor People on the Seashore uses various shades of blue that differ from each other in luminance but hardly at all in color (hue). The melancholy blue color serves an emotional role, but does not affect our recognition of the scene.

- The biological basis for the fact that color and luminance can play distinct roles in our perception of art, or of real life, is that color and luminance are analyzed by different subdivisions of our visual system, and these two subdivisions are responsible for different aspects of visual perception. The parts of our brain that process information about color are located several inches away from the parts that analyze luminance -- as anatomically distinct as vision is from hearing.

Source:
- Includes in-depth explanations of many interesting natural phenomena relating to color (including several interactive applications)
- [http://www.webexhibits.org/causesofcolor/](http://www.webexhibits.org/causesofcolor/)
Factors of visual color sensations
- Brightness / intensity
- Chromaticity / color
- Hue / position in spectrum (red, green, ...)
- Saturation / vividness

Ingredients of a Rainbow

<table>
<thead>
<tr>
<th>Color</th>
<th>Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>violet</td>
<td>380–450 nm</td>
</tr>
<tr>
<td>blue</td>
<td>450–495 nm</td>
</tr>
<tr>
<td>green</td>
<td>495–570 nm</td>
</tr>
<tr>
<td>yellow</td>
<td>570–590 nm</td>
</tr>
<tr>
<td>orange</td>
<td>590–620 nm</td>
</tr>
<tr>
<td>red</td>
<td>620–750 nm</td>
</tr>
</tbody>
</table>
Dynamic Range

- **Dynamic Range:** ratio of maximum to minimum discernible intensity; our range is 10 to $10^{10}$ photons/sec
  - Dynamic range thus $10^{10}$
    - Extraordinary precision achieved via *adaptation*, where the eye acclimates to changes in light over time by adjusting its pupil size
    - At any one moment, human eye has much lower dynamic range of about 10,000:1

- Dynamic range of a display gives you an idea of how many distinct intensities can be depicted on that display
- **Note:** *dynamic range* (ratio of intensities) of a display is not the same as its *gamut* (number of displayable colors)
- Term also applies to audio, printers, cameras, etc.

**Display Examples:**

<table>
<thead>
<tr>
<th>Display Media</th>
<th>Dynamic Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apple 30” HD Display</td>
<td>700 : 1</td>
</tr>
<tr>
<td>CRT</td>
<td>50-200 : 1</td>
</tr>
<tr>
<td>Photographic prints</td>
<td>100 : 1</td>
</tr>
<tr>
<td>Photographic slides</td>
<td>1000 : 1</td>
</tr>
<tr>
<td>Coated paper printed in B/W</td>
<td>100 : 1</td>
</tr>
<tr>
<td>Coated paper printed in color</td>
<td>50 : 1</td>
</tr>
<tr>
<td>Newsprint printed in B/W</td>
<td>10 : 1</td>
</tr>
</tbody>
</table>

- ink bleeding and random noise considerably decreases **DR** in practice

(image from Wikipedia)
Non-linearity of Visual System (1/3)

- What is relationship between perceived brightness $B$ and intensity/luminance $I$? If linear, equal steps in $I$ would yield equal steps in $B$. Visual system is roughly based on ratios, e.g., difference between $I = 0.10$ and $0.11$ is perceived the same as between $0.50$ and $0.55$. Note the difference in relative brightness in a 3-level bulb between $50->100$ watts vs. $100->150$ watts.

- Thus $B = c \log(I)$ to produce equal steps in brightness. Calculate ratio of adjacent $I$ levels for specified number of $I$ values (e.g., 255) – next slide.
Non-linearity of Visual System (2/3)

- To achieve equal steps in brightness, space logarithmically rather than linearly, so that
  \[ \frac{I_{j+1}}{I_j} = \frac{I_j}{I_{j-1}} = r \]

- Use the following relations:
  \[
  I_0 = I_0, \quad I_1 = r I_0, \quad I_2 = r I_1 = r^2 I_0, \quad I_3 = r I_2 = r^3 I_0, \ldots, \\
  I_{255} = r^{255} I_0 = 1
  \]

- Therefore:
  \[
  r = \left( \frac{1}{I_0} \right)^{1/255}, \quad I_j = r^j I_0 = \left( \frac{1}{I_0} \right)^{j/255} I_0 = I_0^{(255-j)/255} \\
  \text{for} \ 0 \leq j \leq 255 \\
  \quad (13.2)
  \]

- In general for \( n+1 \) intensities:
  \[
  r = \left( \frac{1}{I_0} \right)^{1/n}, \quad I_j = I_0^{(n-j)/n} \quad \text{for} \ 0 \leq j \leq n \\
  \quad (13.3)
  \]

- Thus for
  \[ n=3 \ (4\ \text{intensities}) \text{ and } I_0=1/8, \ r=2, \]
  intensity values of 1/8, 1/4, 1/2, and 1
Non-linearity of Visual System (3/3)

- But log function is based on subjective human judgments about relative brightness of various light sources in the human dynamic range.
- In fact, other "power laws" match the subjective curve well enough in this DR, e.g., \( B = c*I^{0.4} \) (or 4.2 for better imagery in a dark room or 0.33 (the value used in the CIE standard)).

- Instead of encoding uniform steps in \( I \) in an image, better to encode roughly equal perceptual steps in \( B \) (using the power law) - called compression.
  - Idea behind encoding analog TV signals and JPEG images.
Non-linearity in Screens - Gamma

- CRTs have a completely separate physics-based power law relating \( V(\text{oltage}) \) and \( I \), roughly
  \[ I = k*V^{(5/2)}; \] power/exponent is called gamma \((\gamma)\)

- Therefore the two power laws essentially cancel and approximate \( V = B \) to recover "I"- allows TV signal to be piped in directly to the analog circuitry

- LCDs have a power law for \( V = f(I) \) that we don't know (perhaps \( I \approx k*V^{2.2} \)), but there's a black box that does lookup to make it LOOK like the CRT power law...except that the power is adjustable (and is also called gamma).

- Gamma used to compensate for different viewing environments and to convert between media and screens, etc. Called gamma correction
Gamma

- Gamma ($\gamma$) is a measure of the nonlinearity of a display
  - Nonlinearity: the response (output) is not directly proportional to the input

- Example: PC monitors have a gamma of roughly 2.5, while Mac monitors have a gamma of 1.8, so Mac images appear dark on PC’s

- Problems in graphics:
  - need to maintain color consistency across different platforms and hardware devices (monitor, printer, etc.)
  - even the same type/brand of monitors change gamma value over time
  - many LCDs have built-in the ability to “fake” a certain gamma level
High Dynamic Range (2/3)

- **High Dynamic Range (HDR):** describes images and display media which compress the visible spectrum to allow for greater contrast between extreme intensities
  - Takes advantage of non-linearities inherent in perception and display devices to compress intensities in a smart fashion
  - Allows a display to artificially depict an exaggerated contrast between really dark darks and really bright brights

(images from Wikipedia)
High Dynamic Range (3/3)

- Can combine photos taken at different exposures into an aggregate HDR image with more overall contrast (higher dynamic range)
  - Generally 32-bit image format (e.g., OpenEXR or RGBE)
  - HDR and tone mapping are hot topics in rendering!

(images from www.hdrsoft.com)
High Dynamic Range (3/3)

- To avoid the inevitable lossy compression of squeezing a huge DR taken by a camera or rendered into, typically, 255 discrete intensity bins, cut DR into sub-intervals and encode each into its own separate image.

- Then use a function (a linear or whatever ramp) to emphasize the most representative sub-interval and either clamp the ones on either side of the chosen one to min and max I values, or even use, say, slow exponentials to allow a little discrimination of values outside the chosen sub-interval. This function is called the **tone map**.

- Expensive displays with many more intensity levels specially designed for HDR images produce incredibly rich images: “Most monitors have a dynamic range of between 300:1 or 400:1, but the Sunnybrook (http://en.wikipedia.org/wiki/Bride's_Hill) HDR display is a staggering 40,000:1.”
Inside a CRT

- Deflection Yoke
- Inner Magnetic Shield
- Electron Gun
- Shadow Mask
- Funnel Glass
- Frame
- Panel Glass
- Phosphor Screen
- Dynamic focus lens
- Elliptical aperture (astigmatism correction) lens
- Shadow mask
- Electron beam guns
- Phosphor dots

Phosphor's light output decays exponentially; refresh at >= 60Hz

Cool pictures: [http://www.pctechguide.com/06crtmon.htm](http://www.pctechguide.com/06crtmon.htm)
Inside an LCD

- Backlight provides (whitish) lighting
- Polarizer filters light, allows only certain light with desired direction to pass
- TFT matrix: transistors and capacitors at each pixel to change the voltage that bends the light
- Liquid Crystal controls direction of light, allow between 0 and 100% through second polarizer
- Color Filter gives each subpixel in (R,G,B) triad its color. Subpixel addressing used in anti-aliasing

Color Terms

- **Hue** distinguishes among colors such as red, green, purple, and yellow

- **Saturation** refers to how pure the color is, how much white/gray is mixed with it
  - red saturated; pink unsaturated
  - royal blue saturated; sky blue unsaturated
  - pastels are less vivid, less intense

- **Lightness**: perceived achromatic intensity of reflecting object

- **Brightness**: perceived intensity of a self-luminous object, such as a light bulb, the sun, or a CRT

- Can distinguish ~7 million colors when samples placed side-by-side (JNDs – Just Noticeable Diffs.)
  - with differences only in hue, λ difference of JND colors are 2nm in central part of visible spectrum, 10 nm at extremes – non-uniformity!
  - about 128 fully saturated hues are distinct
  - eye less discriminating for less saturated light (from 16 to 23 saturation steps for fixed hue and lightness), and less sensitive for less bright light
The effect of (A) passing light through several filters (subtractive mixture), and (B) throwing different lights upon the same spot (additive mixture)

Color Mixing Applets

Additive Mixing Applet:

http://www.cs.brown.edu/exploratories/freeSoftware/repository/edu/brown/cs/exploratories/applets/colorMixing/additive_color_mixing_guide.html

Combined Mixing Applet:

http://www.cs.brown.edu/exploratories/freeSoftware/repository/edu/brown/cs/exploratories/applets/combinedColorMixing/combined_color_mixing_guide.html
Subtractive Mixture

- **Subtractive mixture** occurs with inks for print medium, paints that absorb light.
- In subtractive mixture, light passed by two filters (or reflected by two mixed pigments) is wavelengths passed by first minus that which is subtracted by second.
- First filter passes 420 - 520 nanometers (broad-band blue filter), while second passes 480 - 660 nanometers (broad-band yellow filter). Light that can pass through both is in 480 - 520 nanometers, which appears green.
Additive mixture used to mix R, G, B guns of CRT.

Light passed by two filters (or reflected by two pigments) impinges upon same region of retina.

Pure blue and yellow filtered light on same portion of the screen, reflected upon same retinal region. Image is gray, not green (as in subtractive mixture).
Additive Mixture in Pointillist Art

The Channel at Gravelines (1890) by Georges Seurat

- Color daubs (left detail) mix additively at a distance.
  - Pointillist technique
  - Creates bright colors where mixing pigments darkens (subtractive)
- Sondheim’s “Sunday in the Park with George”: fantastic modern musical exploring Seurat’s color use and theories about light, color, composition.
Complementary Hues – Additive Mixture

**Complementary hues:** Any hue will yield gray if additively mixed (in correct proportion) with opposite hue on color circle. Such hue pairs are complementaries. Of particular importance are the pairs that contain four unique hues: red-green, blue-yellow.

- These complementary “unique” hues play a role in opponent color perception discussed later.
- Note that only for perfect red and green do you get gray – CRT red and green both have yellow components and therefore sum to yellowish gray.
• Gray patches on blue and yellow backgrounds are physically identical, look different.

• Difference in perceived brightness: patch on blue looks brighter than on yellow, result of brightness contrast.

• Also a difference in perceived hue. Patch on blue looks yellowish, while patch on yellow looks bluish. This is color contrast: hues tend to induce their complementary colors in neighboring areas.

For a good applet on this, check out:
http://www.cs.brown.edu/courses/cs092/VA10/HTML/start.html
and click on any Albers Plate link.
Negative Afterimage

- Stare at center of figure for about a minute or two, then look at a blank white screen or a white piece of paper
- Blink once or twice; negative afterimage will appear within a few seconds showing the rose in its “correct” colors (red petals and green leaves)
Specifying (Naming) Color

- How to refer to/name a particular color?
- Compare unknown and sample from a collection
  - colors must be viewed under a standard light source
  - depends on human judgment
- PANTONE® Matching System
  in printing industry

- Munsell color-order system
  - set of samples in 3D space
  - hue, value/lightness, chroma (saturation)
  - equal perceived distances between neighbors

- Artists specify color as tint, shade, tone
  using pure white and black pigments
- Ostwald system is similar

- Later, we’ll look at computer-based models
Psychophysics

• Tint, shade, and tone: subjective. Depend on observer’s judgment, lighting, sample size, context...

• Colorimetry: quantitative; measurement via spectroradiometer (measures reflected/radiated light), colorimeter (measures primary colors), etc.

<table>
<thead>
<tr>
<th>Perceptual term</th>
<th>Colorimetry term</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hue</td>
<td>Dominant wavelength</td>
</tr>
<tr>
<td>Saturation</td>
<td>Excitation purity</td>
</tr>
<tr>
<td>Lightness (reflecting objects)</td>
<td>Luminance</td>
</tr>
<tr>
<td>Brightness (self-luminous objects)</td>
<td>Luminance</td>
</tr>
</tbody>
</table>

• Physiology of vision, theories of perception still active research areas

• **Note**: our auditory and visual processing are very different!
  - both are forms of signal processing
  - visual processing integrates/much more affected by context
  - more than half of our cortex devoted to vision
  - vision probably dominant sense, though it is apparently harder to be deaf than blind
Response to Stimuli (1/3)

- We draw a frequency response curve like this:

\[ f(\lambda) \]

\[ \lambda \]

to indicate how much a receptor responds to light of uniform intensity for each wavelength.

- To compute response to incoming band (frequency distribution) of light, like this:

\[ I(\lambda) \]

\[ \lambda \]

- We multiply the curves, wavelength by wavelength, to compute receptor response to each amount of stimulus across spectrum.
Gray area under product curve represents how much receptor “sees,” i.e., total response to incoming light.

Let’s call this receptor red, then

red perception = $\int R(\lambda)d(\lambda) = \int I(\lambda)f(\lambda)d\lambda$

Response Cell Applet:

Response to Stimuli (3/3)

• Response curve also called filter because it determines amplitude of response (i.e., perceived intensity) of each wavelength

• Where filter’s amplitude is large, lets through most of incoming signal → strong response

• Where filter’s amplitude is low, filters out much/most/all of signal → weak response

• Analogous to impulse response and filtering that you’ll see in the Image Processing Unit
Metamers (1/3)

Different light distributions that produce the same response

- Imagine a creature with one receptor type ("red") with response curve like this:

\[ f(\lambda) \]

- How would it respond to each of these two light sources?

\[ f(\lambda) \]

- Both signals will generate same amount of "red" perception. They are metamers
  - one receptor type cannot give more than one color sensation (albeit with varying brightness)
Metamers (2/3)

• Consider a creature with two receptors ($R_1$, $R_2$)

• Both $I_1$ and $I_2$ are processed by (convolved with) the receptors $R_1$ and $R_2$ to form the same product

• Note that in principle an infinite number of frequency distributions can simulate the effect of $I_2$, e.g., $I_1$
  – in practice, for $I_n$ near tails of response curves, amount of light required becomes impractically large
Metamers (3/3)

- Whenever you have at least two receptors, there are potentially infinite color distributions (metamers) that will generate identical sensations
  - Conversely, no two monochromatic lights can generate identical receptor responses and therefore all look unique

- Observations:
  - If two people have different response curves, they will have different metamers
    - Different people can distinguish between different colors
  - Metamers are purely conceptual
    - Scientific instruments can detect difference between two metameric lights

- Metamer Applet:
Energy Distribution and Metamers

- Spectral color: single wavelength (e.g., from laser); “ROY G. BIV” spectrum

- Non-spectral color: combination of spectral colors; can be shown as continuous spectral distribution or as discrete sum of $n$ primaries (e.g., R, G, B); most colors are non-spectral mixtures

White light spectrum where height of curve is spectral energy distribution

- *Metamers* are spectral energy distributions that are perceived as same “color”
  - each color sensation can be produced by an arbitrarily large number of metamers

Cannot predict average observer’s color sensation from a distribution
Colorimetry Terms

- Can characterize visual effect of any spectral distribution by triple (dominant wavelength, excitation purity, luminance):
  - Dominant wavelength → hue we see; spike of energy $e_2$
  - Excitation purity = ratio of monochromatic light of dominant wavelength, white light to produce color
    - $e_1 = e_2$, excitation purity is 0% (unsaturated)
    - $e_1 = 0$, excitation purity is 100% (fully saturated)
  - Luminance relates to total energy, proportional to integral of (distribution * eye’s response curve (“luminous efficiency function”)) – depends on both $e_1$ and $e_2$
- Note:
  - dominant wavelength of real distribution may not be one with largest amplitude!
  - some colors (purple) have no dominant wavelength
Three Layers of Human Color Perception - Overview

- Receptors in retina (for color matching)
  - Rods, three types of cones (tristimulus theory)
  - Primary colors (only three used for screen images: approx. red, green, blue (RGB))
  - Note: receptors each respond to wide range of frequencies, not just spectral primaries

- Opponent channels (for perception)
  - Other cells in retina and neural connections in visual cortex
  - Blue-yellow, red-green, black-white
  - 4 psychological color primaries*: red, green, blue, and yellow

- Opponent cells (also for perception)
  - Spatial (context) effects, e.g., simultaneous contrast, lateral inhibition

* These colors are called “psychological primaries” because each contains no perceived element of others regardless of intensity. ([www.garysgallery.com/colorprimaries.html](http://www.garysgallery.com/colorprimaries.html))
Receptors in Retina

- Receptors contain photopigments that produce electro-chemical response
- Rods (scotopic): only see grays, work in low-light/night conditions, mostly in periphery
- Cones (photopic): respond to different wavelengths to produce color sensations, work in bright light, densely packed near center of retina (fovea), fewer in periphery
- Young-Helmholtz tristimulus theory\(^1\): 3 cone types, sensitive to all visible wavelengths of light, maximally responsive in different ranges
- Three receptor types can produce a 3-space of hue, saturation and value (lightness/brightness)
- To avoid misinterpretations, S (short), I (intermediate), L (long) often used instead

\(^1\)Thomas Young proposed idea of three receptors in 1801. Hermann von Helmholtz looked at theory from a quantitative basis in 1866. Although they did not work together, theory is called Young-Helmholtz theory since they arrived at same conclusions.
Tristimulus Theory

Spectral-response functions of $f_{\lambda}$ each of the three types of cones on the human retina

Luminous Efficiency Function
$\approx \Sigma f_{\lambda}$ (peak sensitivity at yellow-green (550nm))

- Tristimulus theory does not explain color perception, e.g., not many colors look like mixtures of RGB (violet looks like red and blue, but what about yellow?)

Triple Cell Response Applet:

Hering’s Chromatic Opponent Channels

- Additional neural processing
  - three receptor elements have excitatory and inhibitory connections with neurons higher up that correspond to opponent processes
  - one pole activated by excitation, other by inhibition

- All colors can be described in terms of 4 “psychological color primaries” R, G, B, and Y

- However, a color is never reddish-greenish or bluish-yellowish: idea of two “antagonistic” opponent color channels, red-green and yellow-blue

Light of 450 nm

Hue: Blue + Red = Violet

Each channel is a weighted sum of receptor outputs – linear mapping
Spatially Opponent Cells

- Some cells in opponent channels are also spatially opponent, a type of lateral inhibition (called double-opponent cells)

- Responsible for effects of simultaneous contrast and after images
  - green stimulus in cell surround causes some red excitement in cell center, making gray square in field of green appear reddish

- Plus...
  - color perception strongly influenced by context, training, etc., abnormalities such as color blindness (affects about 8% of males, 0.4% of females)
Nature provides for contrast enhancement at boundaries between regions: edge detection. This is caused by lateral inhibition.
Lateral Inhibition and Contrast

- Receptor cells, A and B, stimulated by neighboring regions of stimulus.
- A receives moderate light. A’s excitation stimulates next neuron on visual chain, cell D, which transmits message toward brain.
- Transmission impeded by cell B, whose intense excitation inhibits cell D. Cell D fires at reduced rate.
- Intensity of cell $c_j = I(c_j)$ is function of $c_j$’s excitation $e(c_j)$ inhibited by its neighbors with attenuation coefficients $\alpha_k$ that decrease with distance. Thus,

$$I(c_j) = e(c_j) - \sum_{k \neq j} \alpha_k e(c_k)$$

- At boundary more excited cells inhibit their less excited neighbors even more and vice versa. Thus, at boundary dark areas even darker than interior dark ones, light areas are lighter than interior light ones.
- Nature’s edge detection
Lecture Roadmap

• Color matching and CIE space
• Color spaces: their rationales, and pros and cons (RGB, HSV, CIE, etc.)
• How color spaces influence color picking
• How to use color: some Dos and Don’ts
Color Matching (1/3)

- Need way to describe colors precisely for industry and science
- Tristimulus Theory makes us want to describe all visible colors in terms of three variables (to get 3D coordinate space) vs. infinite number of spectral wavelengths or special reference swatches...
- Choose three well-defined light colors to be the three variables/“primaries” (R, G, B)
- People sit in a dark room matching colors
Color Matching (2/3)

- But any three primaries R, G and B can’t match all visible colors... (for reasons we’ll be exploring soon)

- Sometimes need to add some R to the sample you are trying to match. Expressed mathematically as “-R”.

http://www.maelabs.ucsd.edu/mae152/handouts/12
Color-matching functions, showing amounts of three primaries needed by average observer to match a color of constant luminance, for all values of dominant wavelength in visible spectrum.

- Note: these are NOT response functions!
- Negative value of $\nu_\lambda$ cannot match, must “subtract,” i.e., add that amount to unknown
- Mixing positive amounts of arbitrary R, G, B primaries provides large color gamut, e.g., display devices, but no device based on a finite number of primaries can show all colors!
CIE Space for Color Matching

- Negative amount of primaries is awkward
- Commission Internationale de l’Éclairage (CIE) defined X, Y, and Z primaries to replace red, green and blue
- \(x_\lambda, y_\lambda,\) and \(z_\lambda,\) color matching functions for these primaries
- Y chosen so that \(y_\lambda\) matches luminous efficiency function
- \(x_\lambda, y_\lambda,\) and \(z_\lambda\) are linear combinations of \(r_\lambda, g_\lambda,\) and \(b_\lambda\)
- \(=> \text{RGB}_i \leftrightarrow \text{XYZ}_i\) conversion via a matrix

The mathematical color matching functions \(x_\lambda, y_\lambda,\) and \(z_\lambda\) for the 1931 CIE X, Y, and Z primaries. They are defined tabularly at 1 nm intervals for color samples that subtend 2° field of view on retina
CIE Chromaticity Diagram (1/4)

- Amounts of X, Y, and Z primaries needed to match a color with spectral energy distribution P(\(\lambda\)):
  
  \[
  X = k \int P(\lambda) x_\lambda d\lambda \\
  Y = k \int P(\lambda) y_\lambda d\lambda \\
  Z = k \int P(\lambda) z_\lambda d\lambda 
  \]

  - in practice use \(\Sigma\)'s

- For given color \(C\), \(C = X X + Y Y + Z Z\)

- Get chromaticity values that depend only on dominant wavelength (hue) and saturation (purity), independent of luminous energy, for a given color, by normalizing for total amount of luminous energy = \((X + Y + Z)\)

  \[
  x = \frac{X}{X + Y + Z}, \quad y = \frac{Y}{X + Y + Z}, \quad z = \frac{Z}{X + Y + Z}
  \]

  \((x, y, z)\) lies on \(X + Y + Z = 1\) plane

  \((x, y)\) determines \(z\) but cannot recover \(X, Y, Z\) from only \(x\) and \(y\).

  Need one more piece of data, \(Y\), which carries luminance data

  \((x, y, Y), X = \frac{x}{y}, \quad Y = Y, \quad Z = \frac{1 - x - y}{y} Y\)

Inset: CIE 1931 chromaticity diagram
CIE Space: International Commission on Illumination

- Now we have a way (specifying a color’s CIE X, Y, and Z values) to precisely characterize any color using only three variables!

- Very convenient! Colorimeters, spectroradiometers measure X, Y, Z values.

- Used in many areas of industry and academia—from paint to lighting to physics and chemistry.

- International Telecommunication Union uses 1931 CIE color matching functions in their recommendations for worldwide unified colorimetry
  - International Telecommunication Union (2000) ITU-R BT.709-4 PARAMETER VALUES FOR THE HDTV STANDARDS FOR PRODUCTION AND INTERNATIONAL PROGRAMME EXCHANGE