Light

• What is light?
  • When light flies through space and interacts with itself (interference), it behaves as a wave (and has a wavelength)
  • When light interacts with matter, it behaves as a particle (photon)

• At any given moment, a light source emits some photons at different frequencies
  • We can plot the emission spectrum of a light source as power vs. wavelength

Newton's experiments

• Newton showed that a prism spreads apart a light source's emission spectrum in space
  • Light emerging from the prism cannot be further decomposed
  • Newton called the colors of these “atomic” lights primaries
  • We call one-color light monochromatic

Measuring the Emission Spectrum

Light sources

• Point sources
  • far away (stars)
  • ideal, easy to model

• Area sources
  • large lamps, sky
  • to calculate incoming energy, need to integrate over the whole area
  • approximate with many point sources

• Volume sources
  • plasma, northern lights
  • approximate with area sources
From source to eye

- Light propagates in a medium
  - straight path in a homogeneous medium
  - absorption
  - scattering (= absorption followed by emission)
- Behavior at a boundary
  - reflection
  - refraction
- Eventually hits the eye

Q: Why is sky blue? The atmosphere scatters the blue light most. The blue scatters down from the rays above us.

Why are sunsets orange? At sunset the light travels longer distance in the atmosphere, blue light scatters away.

Structure of an eye

- **Cornea** - a clear coating over the front of the eye:
  - protects eye
  - provides initial focusing
- **Crystalline lens** - controls the focal distance
  - controlled by muscles called ciliary body
- **Iris**
  - colored annulus with radial muscles
  - controls the aperture called pupil

Lens optics

- **Focal point** - the point where parallel rays converge when passing through a lens.
- **Focal length** - the distance from the lens to the focal point.
- **Diopter** - the reciprocal of the focal length, measured in meters.
  - Example: A lens with a “power” of 10D has a focal length of __10cm__.

Retina

- **Retina**
  - a layer of photosensitive cells covering 200° on the back of the eye
  - **Cones** - responsible for color perception
  - **Rods** - limited to intensity (but 10x more sensitive)
- **Fovea**
  - small region (1 or 2°) at the center of the visual axis
  - the highest density of cones
  - no rods
**Retina, cont.**

- Pictures at increasing nasal distances from the fovea
  
  ![Diagram of Retina](image)

- Many rods are summed together before the information goes to brain
  - lower visual acuity in the periphery

**Photopigments and channels**

- Photopigments
  - are the chemicals in the rods and cones that react to light
  - can respond to a single photon!
  - Rods contain rhodopsin, which has peak sensitivity at 500nm
  - Cones come in three varieties: S, M, L

- Color information is transmitted to the brain in three nerve bundles or channels:
  - Achromatic: \( A = M + L \)
  - Red-green chromatic: \( R/G = M - L \)
  - Blue-yellow chromatic: \( B/Y = S - A \)

**Emission spectrum is not color**

- Recall how much averaging the eye does
  - light is infinite dimensional
  - but color is only 3D
  - or even less (color blindness)

- **Color is a subjective feeling in our brain!**
  - specific for human color vision
    - and really, different for each individual!
  - for an alien, color images could look really weird, "false-color" images
  - but black-and-white images could make more sense to them

**Metamerism**

- Metamerism refers to the situation where
  - two color samples appear to match under one condition but not under another
  - the match is said to be conditional; two samples that conditionally match are said to be a metamer pair

  - Illumination metamerism:
    - two patches appear identical under one light but not under another

  - Observer metamerism:
    - two patches appear identical to one observer but not for another

  - With identical reflectance spectra
    - cannot be metameric - they are an unconditional match
From light to color

Illumination

Reflectance

Light entering eye

Cone absorptions

Cone sensitivities

Relative energy

Wavelength (nm)

Relative sensitivity

Wavelength (nm)

Trichromatic theory

• It is possible to match all of the colors in the visible spectrum by appropriate mixing of three primary colors
• Which primary colors are used is not critically important as long as mixing two of them does not produce the third color

RGB (additive)

CMY (subtractive)

Color variant vision

• Some people have fewer types of cones
  • 3: trichromats
  • 2: dichromats
  • 1: monochromats
• 8% males, 0.6% females

Mach bands

• Human eye is sensitive to small changes in intensity
  • lateral inhibition
• The perceived intensity differences are bigger than the real differences
• These illusory stripes are called Mach bands
**Flicker**

- The photoreceptive cells provide a time-averaged response:
  more photons → more response

- Above a **critical flicker frequency (CFF)**, flashes of light will fuse into a single image

- CFF for humans is about 60 Hz
  - For a bee it's about 300 Hz

**Adaptation**

- The eye can adapt to a large range of illumination
  - change of the size of the pupil (fast)
  - adaptation of the cell response (slow)

<table>
<thead>
<tr>
<th>Background</th>
<th>Luminance (cd/m²)</th>
<th>Change factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moonless overcast night</td>
<td>0.00003</td>
<td>1000x</td>
</tr>
<tr>
<td>Moonless clear night</td>
<td>0.03</td>
<td>100x</td>
</tr>
<tr>
<td>Twilight</td>
<td>3</td>
<td>100x</td>
</tr>
<tr>
<td>Overcast day</td>
<td>300</td>
<td>100x</td>
</tr>
<tr>
<td>Day with sunlit clouds</td>
<td>30,000</td>
<td></td>
</tr>
</tbody>
</table>

**Brightness = Perceptual light intensity**

- We perceive brightness as we do sound:
  - on a **relative** or **logarithmic** scale of the intensity
  - brightness ≈ k * intensity^{0.4}
  - minimum visible relative constant ratio ~1%

- **Example:**
  - The perceived difference between 0.20 and 0.22 is the same as between 0.80 and 0.88

- Ideally, to display **n+1** equally-spaced brightness levels, use the following intensity ratios
  \[
  \frac{I_1}{I_0} = \frac{I_2}{I_1} = \ldots = \frac{I_n}{I_{n-1}}
  \]

**The CIE XYZ System**

- A standard created in 1931 by CIE
  - Commission Internationale de L'Eclairage

- Defined in terms of three color matching functions

- Given an emission spectrum, we can use the CIE matching functions to obtain the x, y and z coordinates
**The CIE Chromaticity Diagram**

- **Chromaticity coordinates** give a notion of color independent of brightness.
- A projection of the plane $x+y+z=1$ yields a *chromaticity value* dependent on:
  - dominant wavelength (= hue), and
  - excitation purity (= saturation).
- Intensity is the distance from the origin.

**More About Chromaticity**

- Dominant wavelengths go around the perimeter of the chromaticity blob:
  - a color’s dominant wavelength is where a line from white through that color intersects the perimeter.
  - some colors, called *nonspectral* colors, don’t have a dominant wavelength.
  (which ones? *colors that mix red and blue* )
- Excitation purity is measured in terms of a color’s position on the line to its dominant wavelength.
- Complementary colors lie on opposite sides of white, and can be mixed to get white:
  - complement of blue is *yellow*.
  - complement of red is *cyan*.

---

**Perceptual (non-)uniformity**

- The XYZ color space is not perceptually uniform!
- Enlarged ellipses of constant color in XYZ space.

**Gamuts**

- Not every output device can reproduce every color.
- A device’s range of reproducible colors is called its *gamut*.
Color spaces for computer graphics

- RGB for display
- CMY (or CMYK) for printing
  - what is the "K" for? Black. Combining cheap CMY inks gives in practice brown, not crisp black.
- HSV (HSB) for user selection
- YCrCb, YIQ for TV and video

Black.

Combining cheap CMY inks gives in practice brown, not crisp black.

HSV (HSB)

- Hue
- Saturation
- Value/Brightness
- More natural for user interaction
- Corresponds to the artistic concepts of tint, shade and tone

YCrCb

- Used in several video formats
  - Y Y axis of CIE, luminance, \(0.299 R + 0.587 G + 0.114 B\)
  - \(C_r\) red chrominance, \(R - Y\)
  - \(C_b\) blue chrominance, \(B - Y\)
- Separate luminance from chrominance
  - on black & white displays, only show Y channel
  - notice that when \(R=G=B\), both chrominances are zero
- Chrominance can be compressed
  - eye is more sensitive to variations in luminance than in chrominance
  - send chrominance only with every other pixel packing ratio is \(Y:C_r:C_b = 4:2:2\)

YIQ

- Used in TV (NTSC) broadcasting
  - Y Y axis of CIE, luminance
  - I intermodulation, major axis of remaining color space
  - Q quadrature, remaining axis
- I and Q are related to \(C_r\) and \(C_b\)
  - still the constraint that when \(R=G=B\), \(I=Q=0\) (zero), so any linear combination is OK
  - scale and rotate
    \[
    \begin{bmatrix}
    I \\
    Q
    \end{bmatrix}
    =
    \begin{bmatrix}
    \cos -33 & -\sin -33 \\
    \sin -33 & \cos -33
    \end{bmatrix}
    \begin{bmatrix}
    0.877 & 0 \\
    0 & 0.493
    \end{bmatrix}
    \begin{bmatrix}
    C_r \\
    C_b
    \end{bmatrix}
    \]
  - eye is more sensitive in the I direction (orange-blue, where flesh tones are) than in the Q direction (purple-green), so you can use less bandwidth on that axis
  - YIQ is broadcast with relative bandwidth ratios 8:3:1
**Luminance from RGB**

- If three sources appear red, green and blue, and have the same radiance in the visible spectrum, then
  - green will appear the brightest of the three because the luminous efficiency function peaks in the green region
  - red will appear less bright, and
  - blue will be the darkest of the three

- If luminance is computed from red, green and blue
  - the green coefficient will be quite large, the red will have an intermediate value, and the blue will be the smallest

- Luminance by NTSC: \(0.299 R + 0.587 G + 0.114 B\)
  - based on phosphors in use in 1953

- Luminance by CIE: \(0.2125 R + 0.7154 G + 0.0721 B\)
  - based on contemporary phosphors

**Cathode ray tubes (CRTs)**

- Consists of:
  - electron gun
  - electron focusing lens
  - deflection plates/coils
  - electron beam
  - anode with phosphor coating

- Electrons “boil off” the heated cathode and shoot towards the anode

- Different phosphors have different:
  - color
    - red: europium yttrium vanadate
    - green: zinc cadmium sulfide
    - blue: zinc sulfide
  - persistence
    - (as long as a few seconds)

- The image must be refreshed to avoid flicker

**Calligraphic displays**

- Also called
  - vector displays
  - stroke displays
  - random-scan displays

- Used until about '85
  - still in oscilloscopes

**Raster displays**

- *raster*, from radere, “to scrape”

- Early '70s, Xerox PARC

- Electron beam traces over screen in raster scan order
  - Each left-to-right trace is a scan line
  - Each spot on the screen is a pixel
  - Turn the beam off to sweep back = retrace, or a blanking interval
Interlacing

- In broadcast television, the refresh cycle is broken into two fields:
  - odd and even
  - each lasting 1/30th second
- Why? To reduce bandwidth, effectively you'll double the frame rate

Additive color mixing

- All colors on a monitor are produced using combinations of red, green, and blue
- A monitor that allows 256 voltage settings for each of R, G, and B is known as a full-color system
- The description of each color in frame buffer memory is known as a channel

Color CRT monitors

- Most color monitors employ shadow mask technology:
  - triads of red, green, and blue phosphors at each pixel
  - three electron guns, one per color
  - shadow mask make each kind of phosphor only “visible” from one gun
- These are also known as RGB monitors

Flat panel displays

- Example: LCD (Liquid Crystal Display)
  - sandwich liquid crystals between two polarized panels
  - the liquid crystals will align themselves with grooves aligned with polarization
  - applying electric charge untwists LCs and polarization blocks the light
  - color is obtained by filtering

![Additive color mixing diagram](image)
Frame buffers

- Intensity of the raster scan beam is modulated according to the contents of a **frame buffer**
- Each element of the frame buffer is associated with a single **pixel** on the screen

Resolution

- The display’s **resolution** is determined by:
  - number of scan lines
  - number of pixels per scan line
  - number of bits per pixel

Examples:
- Bitmapped display: 960 x 1152 x 1b, 1/8 MB
- NTSC TV: 640 x 480 x 16b, 1/2 MB
- Color workstation: 1280 x 1024 x 24b, 4 MB
- Laser-printed page:
  - 300 dpi: 8.5 x 11 x 300\(^2\) x 1b, 1 MB
  - 1200 dpi: 8.5 x 11 x 1200\(^2\) x 1b, 17 MB
- Film: 4500 x 3000 x 30b, 50 MB

Gamma correction

- Intensity of a phosphor has a nonlinear response: \(I = \alpha \delta^\gamma\)
  - \(\delta\) rate of electrons striking phosphors
  - proportional to the value stored in frame buffer
  - \(\gamma\) (gamma), depends on
    - kind of phosphor and how it was deposited on CRT
    - needs to be measured experimentally (typically 2.3 – 2.8)

- To fix this problem, need to precorrect
  - raise the colors to power of \(1/\gamma\) to cancel out \(\gamma\)
  \(I = \alpha (c/255.0)^{1/\gamma} = \alpha (c/255.0)\)
  - often done using look-up tables

- If gamma is not right, both colors and intensities shift
  - example: color is (0, 255, 127)
  - if this is not gamma corrected, red channel remains 0, green 255, but blue is decreased by the display

Brightness and contrast

- Brightness and contrast knobs control \(\alpha\) and \(\gamma\). \(I = \alpha \delta^\gamma\)
- Which one controls which?
Specifying colors

• The number of color choices depends on the amount of frame buffer storage allocated per pixel.

• Q: How many colors can be displayed in one frame with:
  - 3 bits per pixel? \( 2^3 = 8 \)
  - 8 bits per pixel? \( 2^8 = 256 \)
  - 16 bits per pixel? \( 2^{16} = 64 \times 1024 \approx 64 \text{ thousand} \)
  - 24 bits per pixel? \( 2^{24} = 16 \times 1024 \times 1024 \approx 16 \text{ million} \)

• You can also use bits on frame buffer for other things
  - alpha for, e.g., transparency
  - z for depth ordering
  - …

RGB frame buffer

• The term true-color is sometimes used to refer to systems where the frame buffer directly stores the values of each channel.

Color tables

• Color tables allow more color versatility when you only have a few bits per pixel. You get to select a small palette from a large number of available colors.

• Each frame buffer element is now an index into the color table, where the actual values of each channel are stored.
  - Color table entries can be changed in software.

Color tables on 24-bit systems

• Even full-color systems often use color tables
  - a separate color table for each 8 bit channel

• Q: Why would you want this capability?
  - Gamma and other monitor corrections
  - Special effects (false coloring)
  - Hardware color space conversions (YIQ->RGB)
**Double-buffering**

- Q: What happens when you write to the frame buffer while it is being displayed on the monitor?
- **Double-buffering** provides a solution

**Depth cues: classification**

- Optical vs. ocular
  - picture vs. physical status of eye

- Binocular vs. monocular
  - one or two eyes

- Static vs. dynamic
  - can the observer move

- Quantitative vs. qualitative
  - can you make metric measurements or just relative comparisons

**Depth cues**

- Accommodation
  - distance of focus
  - oc, mon, stat, quan

- Convergence
  - how do you aim the eyes
  - oc, bin, stat, quan

- Binocular disparity
  - parallax between two images
  - opt, bin, stat, quan

- Motion parallax
  - how fast do details move when observer moves around (close ones move faster)
  - opt, mon, dyn, quan

- Texture accretion / deletion
  - occlusion and disocclusion of texture when observer moves around
  - opt, mon, dyn, qual

- Convergence of parallel lines
  - railroad tracks converge when far away
  - opt, mon, stat, quan

- Position relative to horizon
  - assuming objects lie on ground, relative vertical position w.r.t. horizon is a good depth cue
  - opt, mon, stat, quan

- Size
  - relative size of similar objects indicates relative depth
  - opt, mon, stat, quan

- Texture gradient
  - uniform texture foreshortens with distance
  - opt, mon, stat, quan

- Occlusion
  - object partially hides another, gives relative depth order
  - opt, mon, stat, qual
Depth cues

- Shading and shadows: objects of uniform color are shaded differently based on surface orientation, so you get idea of object shape and therefore of the relative distance of its parts. Cast shadows give extra information, e.g., whether object touches ground or not.

- Aerial perspective: the effect of atmosphere. Distant objects appear more blue, less saturated, less contrasted, more blurry.

Neurological theory of esthetics

- Ramachandran & Hirstein 1999

- Address three questions:
  - Which rules of art make something visually pleasing?
  - What forms do the rules have and why did they evolve?
  - What brain mechanisms are involved?

- Eight laws:
  - peak shift principle
  - grouping and binding
  - isolation of a single visual module
  - problem solving
  - contrast extraction
  - symmetry
  - generic viewpoint
  - use of metaphor

The peak shift principle

- Supernormal stimuli can excite brain more than normal ones.
- Caricatures exaggerate differences from norm.
- A rat experiment: teach a rat that rectangles (aspect ratio 3:2) are better than squares, they will respond even more positively for thinner rectangles (4:1).
- Reward and non-reward stimulus must be close enough.
  - otherwise won't work.
  - will just look weird.

Grouping

- Factors:
  - similarity
    - shape, color (color stronger)
  - proximity
    - physically close
  - common fate
    - things that move together
  - continuity
    - form or joined by a line
  - closure
    - form closed regions of space
  - past experience
    - interpretation based on surrounding objects
 Binding and problem solving

- Perceptual binding
  - initially difficult to understand or ambiguous
  - discovery gives a pleasurable “aha” sensation
  - once you have one interpretation, the previous one is difficult to hold

 Isolation of a single visual module

- Isolate a visual modality before applying peak shift stimulus
  - movement
  - color
  - form
  - Can use to
    - focus attention
    - imply motion where there is none

 Contrast extraction

- Suggestion:
  - visual system allocates attention to contrasting regions since information generally resides there
  - so contrast is more interesting, therefore more pleasing
  - intensity contrast
  - size contrast
  - position contrast (one inside other)
  - contrast size and number

 Symmetry

- A special case of grouping
- Virtually all designed objects show at least one axis of symmetry
- Both humans and animals prefer bilateral symmetry when choosing mate
  - indication of youthfulness and health
  - with patterns, it is easier to spot the out-of-place and potentially dangerous
**Generic viewpoint**

- A canonical viewpoint is preferred
- Predictors
  - significance of visible features for a given observer
  - stability of the view to small perturbations
  - extent to which features are occluded
- Artists’ rules
  - pick an off-axis view from a natural eye height
  - avoid 45 deg angles
  - have projections of front/side/top to have relative areas of 4/2/1

**Use of metaphor**

- Metaphor
  - an implied comparison between two things of unlike nature that still have something in common
  - suggest a likeness or analogy
- Can use to
  - emphasize subject
  - enhance emotional response to image
- Visual puns and metaphors enhance art