White Light
• sun or light bulbs emit all frequencies within visible range to produce what we perceive as "white light"

Sunlight Spectrum
• spectral distribution: power vs. wavelength

Continuous Spectrum
• sunlight
• various "daylight" lamps

Line Spectrum
• ionized gases
• lasers
• some fluorescent lamps

Electromagnetic Spectrum
- 700 nm to 400 nm
- AM radio / microwave, ultraviolet, gamma rays
- RED, INFRARED, X-RAYS
- Shortest to longest wavelengths
- Color temperature
- Blackbody radiation

Blackbody Radiation
- black body
- dark material, so that reflection can be neglected
- spectrum of emitted light changes with temperature
- cold: mostly infrared
- hot reddish
- very hot: bluish
- demo:

Light Sources
- common light sources differ in kind of spectrum they emit:
  - continuous spectrum
    - energy is emitted at all wavelengths
      - blackbody radiation
      - tungsten light bulbs
      - certain fluorescent lamps
      - sunlight
      - electrical arcs
      - line spectrum
        - energy is emitted at certain discrete frequencies

Additive vs. Subtractive Colors
- additive: light
  - monitors, LCDs
  - RGB model
- subtractive: pigment
  - printers
  - CMY model
  - dyes absorb light

Component Color
- component-wise multiplication of colors
  - (a0,a1,a2) * (b0,b1,b2) = (a0*b0, a1*b1, a2*b2)
- why does this work?
  - must dive into light, human vision, color spaces

Basics of Color
- elements of color:
  - physics
  - illumination
  - electromagnetic spectra
  - reflection
  - material properties
  - surface geometry and microgeometry
  - polished versus matte versus brushed
  - perception
  - physiology and neurophysiology
  - perceptual psychology

Basics of Color
- fourth component for transparency
  - (r,g,b,α)
  - fraction we can see through:
    - c = αc0 + (1-α)c1
  - as we saw in blending/compositing already

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White Light and Color
- when white light is incident upon an object, some frequencies are reflected and some are absorbed by the object
- combination of frequencies present in the reflected light that determines what we perceive as the color of the object

Hue
- hue (or simply, "color") is dominant wavelength/frequency
- integration of energy for all visible wavelengths is proportional to intensity of color

Saturation or Purity of Light
- how washed out or how pure the color of the light appears
- contribution of dominant light vs. other frequencies producing white light
- saturation: how far is color from grey
- pink is less saturated than red
- sky blue is less saturated than royal blue

Intensity vs. Brightness
- intensity: physical term
- measured radiant energy emitted per unit of time, per unit solid angle, and per unit projected area of the source (related to the luminance of the source)
- lightness/brightness: perceived intensity of light
- nonlinear

Perceptual vs. Colorimetric Terms
- Perceptual
  - Hue
  - Saturation
  - Lightness
  - Brightness
- Colorimetric
  - Dominant wavelength
  - Excitation purity
  - Luminance

Tristimulus Theory of Color Vision
- Although light sources can have extremely complex spectra, it was empirically determined that colors could be described by only 3 primaries
- Colors that look the same but have different spectra are called metamer

Physiology of Vision
- Center of retina is densely packed region called the fovea.
- Cones much denser here than the periphery

Color Spaces
- three types of cones
  - L or R, most sensitive to red light (610 nm)
  - M or G, most sensitive to green light (560 nm)
  - S or B, most sensitive to blue light (450 nm)

Metamers
- a given perceptual sensation of color derives from the stimulus of all three cone types

CIE Color Space
- CIE defined 3 "imaginary" lights X, Y, Z
- any wavelength λ can be matched perceptually by positive combinations

Measured vs. CIE Color Spaces
- X, Y, Z form 3D shape
- project X, Y, Z on X+Y+Z=1 plane for 2D color space
- chromaticity diagram
  - separate color from brightness
  - x = X / (X+Y+Z)
  - y = Y / (X+Y+Z)

Foveal Vision
- hold out your thumb at arm’s length

Negative Lobes
- sometimes need to point red light to shine on target in order to match colors
  - equivalent mathematically to "removing red"
  - but physically impossible to remove red from CRT phosphors
- can’t generate all other wavelengths with any set of three positive monochromatic lights!
- solution: convert to new synthetic coordinate system to make the job easy
CIE “Horseshoe” Diagram Facts
- all visible colors lie inside the horseshoe
- result from color matching experiments
- spectral (monochromatic) colors lie around the border
- straight line between blue and red contains purple tones
- colors combine linearly (i.e. along lines), since the xy-plane is a plane from a linear space

Blackbody Curve
- illumination:
  - candle 2000K
  - A: Light bulb 3000K
  - sunset/sunrise 2000K
  - D: daylight 6500K
  - overcast day 7000K
  - lightning >20,000K

CIE “Horseshoe” Diagram Facts
- can choose a point C for a white point
- corresponds to an illuminant
- usually on curve swept out by black body radiation spectra for different temperatures
- two colors are complementary relative to C when are located on opposite sides of line segment through C
- so C is an affine combination of the two colors
- extend line from C through color to edge of diagram
- some colors (i.e. purples) do not have a dominant wavelength, but their complementary color does

Color Interpolation, Dominant & Opponent Wavelength
- definition
- achromatic axis
- R-G and Y-B axis
- separate lightness from chroma channels
- first level encoding
- linear combination of LMS
- before optic nerve
- basis for perception
- “color blind” = color deficient
- degraded/no acuity on one axis
- 8%-10% men are red/green deficient

Luminance vs. Intensity
- luminance
  - Y of YIQ
  - \[ 0.299R + 0.587G + 0.114B \]
  - captures important factor
- intensity/brightness
  - \[ I/\sqrt{V} \] of HSI/HSV
- \[ 0.333R + 0.333G + 0.333B \]
- not perceptually based

Opponent Color
- definition
  - achromatic axis
  - R-G and Y-B axis
  - separate lightness from chroma channels
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### Color/Lightness Constancy
- Color perception depends on surrounding colors in close proximity.
  - Simultaneous contrast effect.
- Illumination under which the scene is viewed.

### Stroop Effect
- Red
- Blue
- Orange
- Purple
- Green
- Interplay between cognition and perception.

### Color Constancy
- Automatic "white balance" from change in illumination.
- Vast amount of processing behind the scenes.
- Colorimetry vs. perception.