University of British Columbia

CPSC 414 Computer Graphics

Color

Week 10, Wed 5 Nov 2003

Readings

- Chapter 1.4: color
- plus supplemental reading:
  - A Survey of Color for Computer Graphics, Maureen Stone, SIGGRAPH Course Notes 2001
  - pages 4-24 required
  - http://graphics.stanford.edu/courses/cs448b-02-spring/04cdrom.pdf

News

- yet more extra office hours
  - Tue 11-1 (AW xtra)
  - Wed 1-2 (AW lab), 2-3 (PZ lab)
  - Thu 11-1 (AW, AG xtra) 12-1 (AG lab)
  - Fri 10-11 (AG lab), 11:30-1:30 (AW, AG xtra)
- I'm at a conference Fri pm – Mon pm
  - guest lecture Monday: Ahbijeet Ghosh
  - my personal mail response will be slow
  - use newsgroup or email to TAs
    - if can't post remotely, try unsub/resub or port forward
- homework 1 pickup again end of class

Picking Hints

- use OpenGL picking to find correct face
- plane: vectors from face verts, construct normal
- 4 lines: gluUnProject
  - rect around pick xy point, z = 0 and z = 1
  - visual debugging: try drawing line in scene
  - print out matrices, see if look right
    - make sure to grab them when they're correct
    - confusing glGetDoublev params: MODELVIEW_MATRIX
- calculcate line/plane intersection
  - nudge outwards along normal

Flying Hints

- spec: move wrt current camera coord sys
  - gluLookAt difficult
    - transform from roll/pitch/yaw/forward to eye/lookat/up
  - cumulative Euler angles difficult
    - transform from current axes (x/y/z) to new basis vector set in world coords
      - not even just each mouse drag: each transformation!
      - roll/pitch/yaw: last one wrong no matter which order you pick
      - heading not same as direction of motion
  - incremental Euler angles easy
    - want to just use current camera coord sys axes!

Incremental Euler Approach

- assume you know current coord sys
  - drag means motion wrt simple axis (x, y, or z)
- storing roll/pitch/yaw/forward values
  - do not keep cumulative values!
  - do purely incremental
    - only nonzero during drag
    - all three axes won't be active at once
- apply new incremental motion so change to new coord sys

Matrix Stack As Calculator, Storage

- if not saving cumulative values, how do you know where you are?
  - if careful to segregate modelling transforms with push/pop, current viewing transformation stored in matrix stack!
  - don't just erase with glIdentity
  - reuse stack values from last frame instead

Matrix Stack As Calculator, Storage

- transformation order problem
  - stack only supports p' = Current Incr p
  - want p' = Incr Current p
- read out stack into temporary matrix
  - glGetDoublev, just like when you unproject
  - then wipe stack, issue incr, issue current
  - now stack has correct new value, life is good
- uses stack to both calculate and to store

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Visibility recap

The Z-Buffer Algorithm

- augment color framebuffer with Z-buffer or depth buffer which stores Z value at each pixel
  - at frame beginning, initialize all pixel depths to ∞
  - when rasterizing, interpolate depth (Z) across polygon and store in pixel of Z-buffer
  - suppress writing to a pixel if its Z value is more distant than the Z value already stored there
  - depth-buffer essentially stores $1/z$, rather than z

Z-Buffer Pros

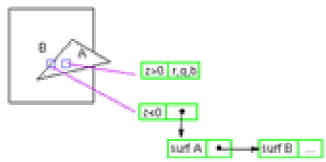
- simple!!!
- easy to implement in hardware
- polygons can be processed in arbitrary order
- easily handles polygon interpenetration

Z-Buffer Cons

- lots of memory (e.g. 1280x1024x32 bits)
  - with 16 bits cannot discern millimeter differences in objects at 1 km distance
- Read-Modify-Write in inner loop requires fast memory
- hard to do analytic antialiasing
  - we don't know which polygon to map pixel back to
- hard to simulate translucent polygons
  - we throw away color of polygons behind closest one

The A-Buffer

– antialiased, area-averaged accumulation buffer
  • z-buffer: one visible surface per pixel
  • A-buffer: linked list of surfaces



Hidden Surface Removal

– image-space algorithms
  • Z-buffer, Warnock's
  • perform visibility test for every pixel independently
  • performed late in rendering pipeline, resolution dependent
– object-space algorithms
  • painter's algorithm: depth-sorting, BSP trees
  • determine visibility on a polygon level in camera coordinates
  • early in rendering pipeline (after clipping)
  • resolution independent
  • expensive

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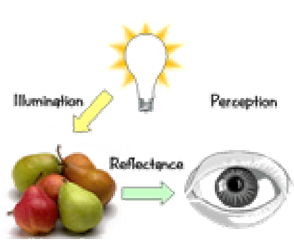
Color

Color

To understand how to make realistic images, we need a basic understanding of the physics and physiology of vision. Here we step away from the code and math for a bit to talk about basic principles.

Basics Of Color

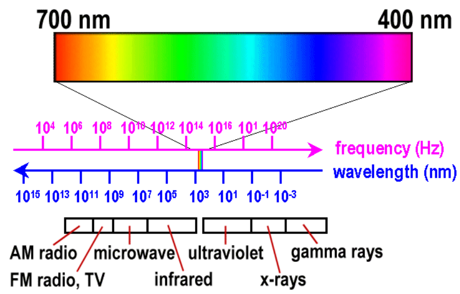
• elements of color:



Basics of Color

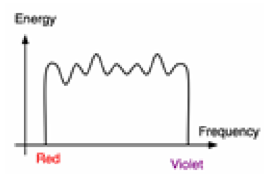
• Physics:
  – Illumination
    • Electromagnetic spectra
  – Reflection
    • Material properties
    • Surface geometry and microgeometry (i.e., polished versus matte versus brushed)
• Perception
  – Physiology and neurophysiology
  – Perceptual psychology

Electromagnetic Spectrum

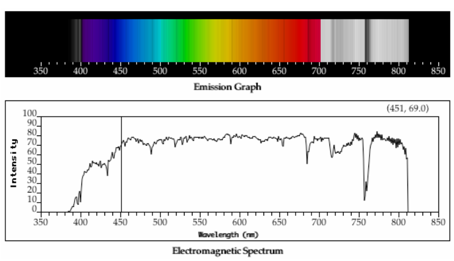


White Light

- Sun or light bulbs emit all frequencies within the visible range to produce what we perceive as the "white light"



Sunlight Spectrum

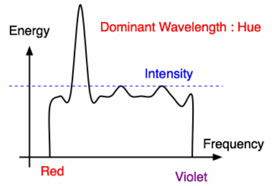


White Light and Color

- 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 determinses what we perceive as the color of the object

Hue

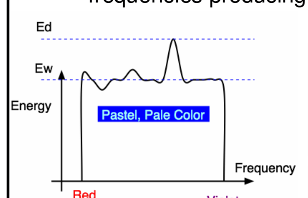
- hue (or simply, "color") is dominant wavelength

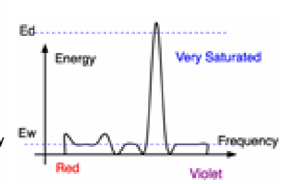


  – integration of energy for all visible wavelengths is proportional to intensity of color

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





Intensity, Brightness

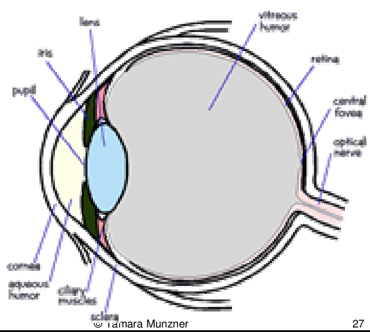
- intensity : radiant energy emitted per unit of time, per unit solid angle, and per unit projected area of the source (related to the luminance of the source)
- brightness : perceived intensity of light

Humans and Light

- when we view a source of light, our eyes respond respond to
  - hue: the color we see (red, green, purple)
    - dominant frequency
  - saturation: how far is color from grey
    - how far is the color from gray (pink is less saturated than red, sky blue is less saturated than royal blue)
  - brightness: how bright is the color
    - how bright are the lights illuminating the object?

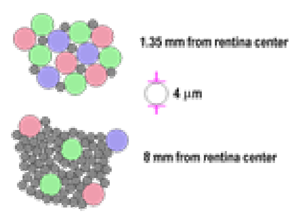
Physiology of Vision

- The eye:
- The retina
  - Rods
  - Cones
    - Color!



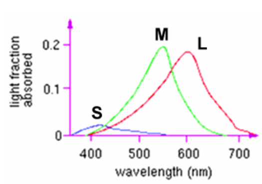
Physiology of Vision

- The center of the retina is a densely packed region called the *fovea*.
  - Cones much denser here than the *periphery*



Trichromacy

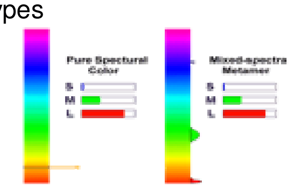
- three types of cones
  - L or R, most sensitive to red light (610 nm)
  - M or G, most sensitive to green light (560 nm)
  - S or B, most sensitive to blue light (430 nm)



  - color blindness results from missing cone type(s)

Metamers

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



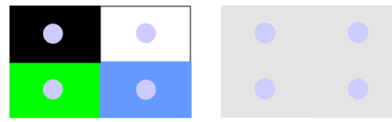
- identical perceptions of color can thus be caused by very different spectra

Metamer Demo

- http://www.cs.brown.edu/exploratories/freeSoftware/catalogs/color_theory.html

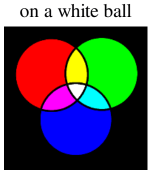
Adaptation, Surrounding Color

- color perception is also affected by
  - adaptation (stare at a light bulb… don't)
  - surrounding color/intensity:
    - simultaneous contrast effect



Combining Colors

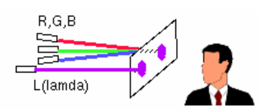
Additive (RGB)
Shining colored lights
on a white ball

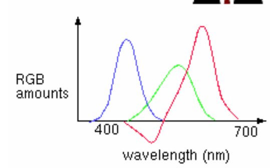


Subtractive (CMYK)
Mixing paint colors and
illuminating with white light

Color Spaces

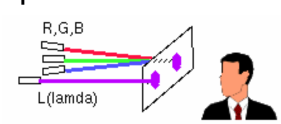
- Three types of cones suggests color is a 3D quantity. How to define 3D color space?
- Idea:
  - Shine given wavelength (λ) on a screen
  - User must control three pure lights producing three other wavelengths (say R=700nm, G=546nm, and B=436nm)
  - Adjust intensity of RGB





Color Spaces

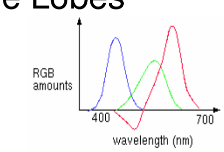
- Three types of cones suggests color is a 3D quantity. How to define 3D color space?



- Idea:
  - Shine given wavelength (λ) on a screen
  - User must control three pure lights producing three other wavelengths (say R=700nm, G=546nm, and B=436nm)
  - Adjust intensity of RGB until colors are identical

Negative Lobes

- Exact target match with phosphors not possible



- Some red had to be added to target color to permit exact match using "knobs" on RGB intensity output of CRT
- Equivalently (theoretically), some red could have been removed from CRT output
- Figure shows that red phosphor must remove some cyan for perfect match
- CRT phosphors cannot remove cyan, so 500 nm cannot be generated

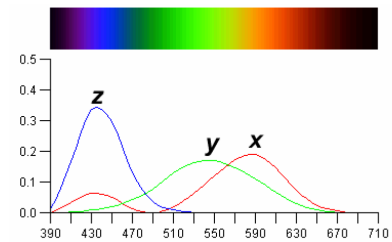
Negative Lobes

- can't generate all other wavelenths with any set of three monochromatic lights!
- solution: convert to new synthetic coordinate system to make the job easy

CIE Color Space

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

Note that:
X ~ R
Y ~ G
Z ~ B

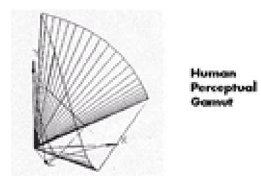


CIE Color Space

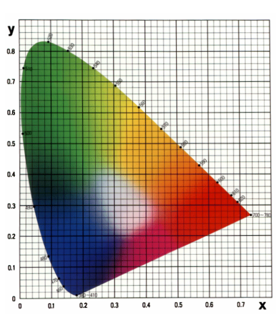
- Target spectrum matched by finding corresponding X, Y, and Z quantities
  - Integrate product of spectral power and each of the three matching curves over all wavelengths

CIE Color Space

- The gamut of all colors perceivable is thus a three-dimensional shape in X,Y,Z
- Color = X'*X* + Y'*Y* + Z'*Z*



CIE Chromaticity Diagram (1931)

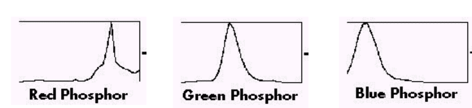


For simplicity, we often project to the 2D plane X'+Y'+Z'=1

$X' = X' / (X'+Y'+Z')$
$Y' = Y' / (X'+Y'+Z')$
$Z' = 1 - X' - Y'$

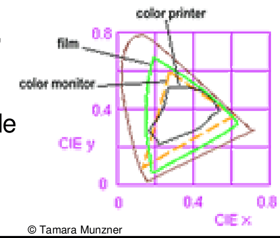
Device Color Gamuts

- Since X, Y, and Z are hypothetical light sources, no real device can produce the entire gamut of perceivable color
- Example: CRT monitor



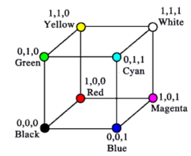
Device Color Gamuts

- We can use the CIE chromaticity diagram to compare the gamuts of various devices:
- Note, for example, that a color printer cannot reproduce all shades available on a color monitor



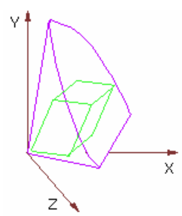
RGB Color Space (Color Cube)

- Define colors with (r, g, b) amounts of red, green, and blue



RGB Color Gamuts

- The RGB color cube sits within CIE color space something like this:



Converting Color Spaces

- Simple matrix operation:

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = \begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

- The transformation $\mathbf{C_2} = \mathbf{M}^{-1}{}_{2}\,\mathbf{M_1}\,\mathbf{C_1}$ yields RGB on monitor 2 that is equivalent to a given RGB on monitor 1

YIQ Color Space

- *YIQ* is the color model used for color TV in America. *Y* is brightness, *I* & *Q* are color
  - Note: *Y* is the same as CIE's *Y*
  - Result: Use the Y alone and backwards compatibility with B/W TV!
  - These days when you convert RGB image to B/W image, the green and blue components are thrown away and red is used to control shades of grey (usually)

Converting Color Spaces

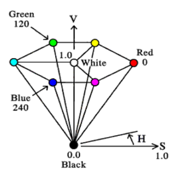
- Converting between color models can also be expressed as such a matrix transform:

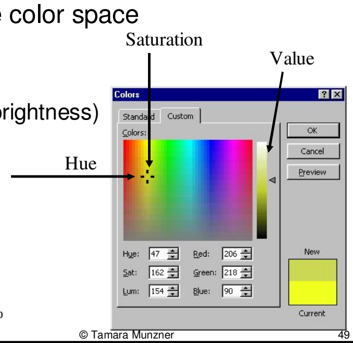
$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.30 & 0.59 & 0.11 \\ 0.60 & -0.28 & -0.32 \\ 0.21 & -0.52 & 0.31 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

- Note the relative unimportance of blue in computing the Y

HSV Color Space

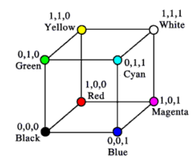
- A more intuitive color space
  - H = Hue
  - S = Saturation
  - V = Value (or brightness)





Perceptually Uniform Color Space

- Color space in which Euclidean distance between two colors in space is proportional to the perceived distance
  - CIE, RGB, not perceptually uniform
    - Example with RGB



Pick up Homework 1

- take 2