CS 5600

Introduction to Computer Graphics

http://www.eng.utah.edu/~cs5600/

Prof: Chuck Hansen

Goal: have fun and learn graphics!

CS 5600

- Class mailing list: cs5600@list.eng.utah.edu
- Sign up: https://sympa.eng.utah.edu/sympa/info/cs5600
- Text: OpenGL Programming Guide
  "Red Book"
  supplemental reading material
  - » DDA – Line Drawing
  - » Ray Tracing

CS 5600

- Grading:
  70% homework
  25% exams
  5% class participation (ask questions, respond to questions)
- Cheating: DON'T share code! DON'T grab code off the web!
- Late penalty: -20%/day but 4 one-day grace periods.

CS 5600

- What will we do?
  - Color
  - DDA algorithms (equ. into algs)
  - Scan conversion
  - Transformations
  - Projections
  - Polygon rendering
  - Texture mapping
  - Ray tracing

Prereqs:

- Normalized Vector?
- Matrix multiply?
- Vector multiply?
- Dot-product? (what is it?)

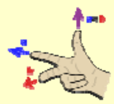
Prereqs:

- Normalized Vector?
- Matrix multiply?
- Vector multiply?
- Dot-product? (what is it?)

$$\mathbf{a} \cdot \mathbf{b} = |\mathbf{a}|\,|\mathbf{b}| \cos\theta$$

Prereqs:

- Cross Product?
  - Properties?



Prereqs:

- Cross Product?
  - Properties?
  - Compute?

$$\mathbf{a} \times \mathbf{b} = \det \begin{bmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \end{bmatrix}.$$

Cross Product

V1 = [3, -1, 0] V2 = [4, -3, 1]

x	y	z
3	-1	0
4	-3	1

Det:

Cross Product

V1 = [3, -1, 0] V2 = [4, -3, 1]

x	y	z
3	-1	0
4	-3	1

Det: -1 - 0 ,

Cross Product

V1 = [3, -1, 0] V2 = [4, -3, 1]

x	y	z
3	-1	0
4	-3	1

Det: -1 , 3 - 0 ,

X WRONG!

Cross Product

V1 = [3, -1, 0] V2 = [4, -3, 1]

x	y	z
3	-1	0
4	-3	1

Det: -1 , 0 - 3 ,

Cross Product

V1 = [3, -1, 0]   V2 = [4, -3, 1]

x y z
3 -1 0
4 -3 1

Det: -1, -3, -9 - (-4)

Cross Product

V1 = [3, -1, 0]   V2 = [4, -3, 1]

x y z
3 -1 0
4 -3 1

Det: -1, -3, -5

Cross Product Sarrus' scheme

V1 = [3, -1, 0]   V2 = [4, -3, 1]

x y z x y z
3 -1 0 3 -1 0
4 -3 1 4 -3 1

Det:

Cross Product Sarrus' scheme

V1 = [3, -1, 0]   V2 = [4, -3, 1]

x y z x y z
3 -1 0 3 -1 0
4 -3 1 4 -3 1

Det: -1 - 0 ,

Cross Product Sarrus' scheme

V1 = [3, -1, 0]   V2 = [4, -3, 1]

x y z x y z
3 -1 0 3 -1 0
4 -3 1 4 -3 1

Det: -1, 0 - 3 ,

Cross Product Sarrus' scheme

V1 = [3, -1, 0]   V2 = [4, -3, 1]

x y z x y z
3 -1 0 3 -1 0
4 -3 1 4 -3 1

Det: -1, -3, -9 - (-4) ,

Cross Product Sarrus' scheme

V1 = [3, -1, 0]   V2 = [4, -3, 1]

x	y	z	x	y	z
3	-1	0	3	-1	0
4	-3	1	4	-3	1

Det: -1, -3, -5

Line Equations

- Explicit form:
  y = mx + b
- Implicit form:
  f(x,y) = Ax + By + C = 0
- Parametric form:
  $P(x,y) = P_0 + t\,D$

Line Equations

Show: y = mx + b equivalent to
$P(x,y) = P_0 + t\,\vec{D}$

For P_1P_2 (assume b=0) :
y – y1 = ((y2 – y1)/(x2 – x1)) (x – x1)
x = ((x2 – x1)/(y2 – y1)) (y – y1) + x1

Line Equations

$P(x,y) = P_0 + t\,\vec{D}$ For $\overline{P_1P_2}$:
x = x1 + t (x2 – x1)
y = y1 + t (y2 – y1)
t = (x – x1) / (x2 – x1)
y = y1 + [(x – x1) / (x2 – x1)] (y2 – y1)
y – y1 = (x – x1) [(y2 – y1) / (x2 – x1)]

x = ((x2 – x1)/(y2 – y1)) (y – y1) + x1

Color

Lecture Set 1

CS5600 ***Computer Graphics***
Modified from Rich Riesenfeld

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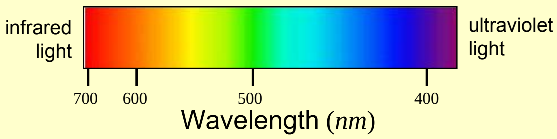
Color

- Color is complicated!
  - Highly nonlinear
  - No single model to explain all
- Many simplistic models, explanations
- Many myths
- Much new knowledge

Wavelength Spectrum



- Seen in physics, physical phenomena (rainbows, prisms, etc)
- 1 Dimensional color space

Wavelength Spectrum

Color Space

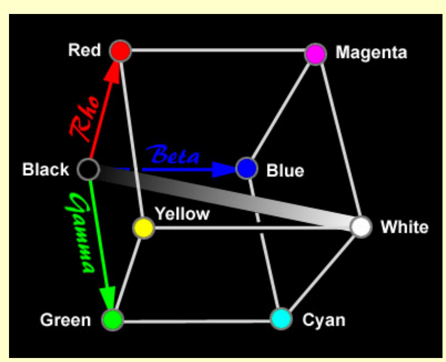
- "Navigating," moving around in a *color space*, is tricky
- Many color representations (*spaces*)
- Can you get to a nearby color?
- Can you predictably adjust a color?

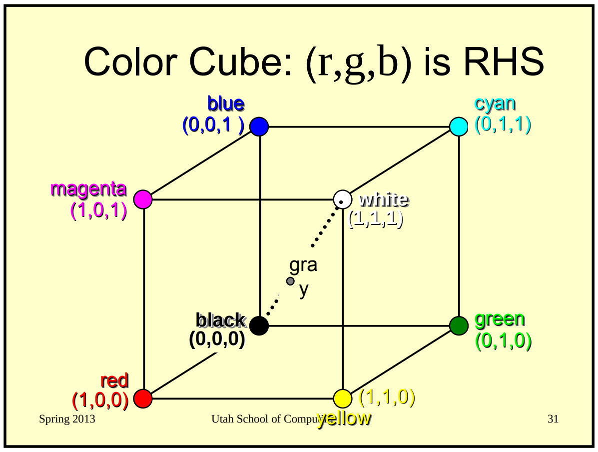
Color Spaces

- Device-derived
  - convenient for describing display device levels
  - RGB, CMY
- Intuitive (transformations)
  - based in familiar color description terms
  - HSV, HSI
- Perceptually based
  - device independent, perceptually uniform
  - CIELUV, CIELAB, Munsell

R-G-B Color Space

- Convenient colors (screen phosphors)
- Decent coverage of the human color
- Not a particularly good basis for human interaction
  - Non-intuitive
  - Non-orthogonal (perceptually)




Color Cube: (r,g,b) is RHS
blue
(0,0,1)
cyan
(0,1,1)
magenta
(1,0,1)
white
(1,1,1)
gra
y
black
(0,0,0)
green
(0,1,0)
red
(1,0,0)
(1,1,0)
yellow
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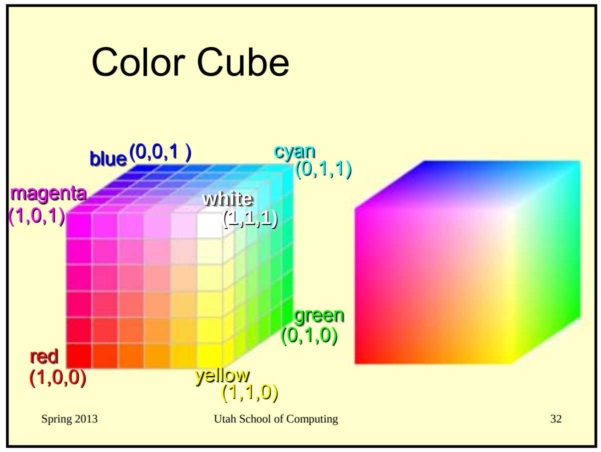
Color Cube
blue (0,0,1)
cyan
(0,1,1)
magenta
(1,0,1)
white
(1,1,1)
green
(0,1,0)
red
(1,0,0)
yellow
(1,1,0)
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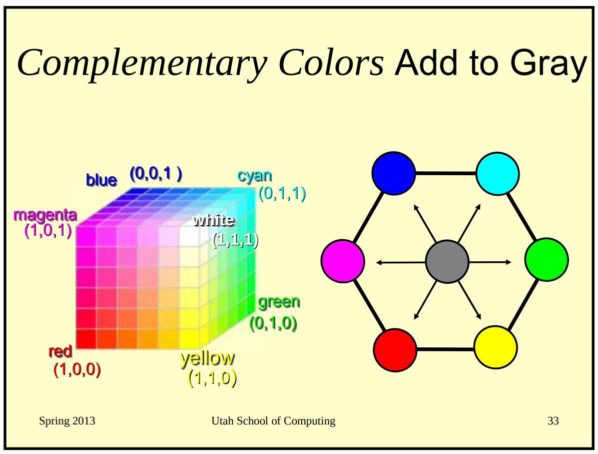
Complementary Colors Add to Gray
blue (0,0,1)
cyan
(0,1,1)
magenta
(1,0,1)
white
(1,1,1)
green
(0,1,0)
red
(1,0,0)
yellow
(1,1,0)
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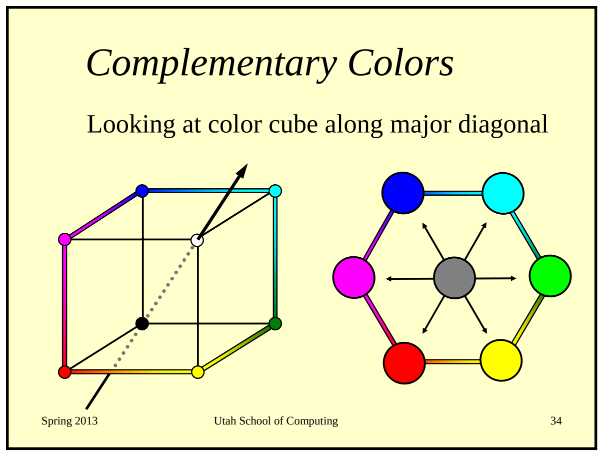
Complementary Colors
Looking at color cube along major diagonal
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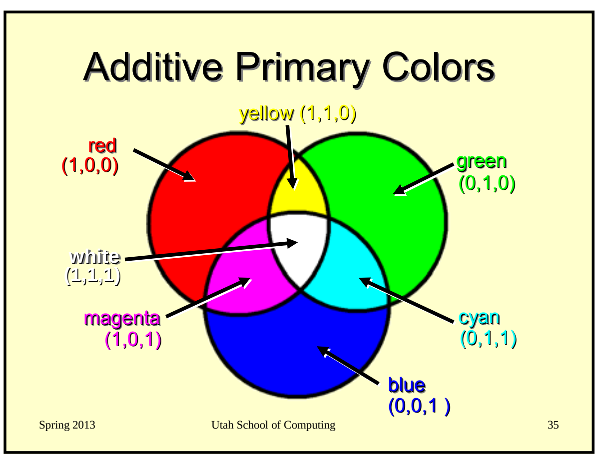
Additive Primary Colors
yellow (1,1,0)
red
(1,0,0)
green
(0,1,0)
white
(1,1,1)
magenta
(1,0,1)
cyan
(0,1,1)
blue
(0,0,1)
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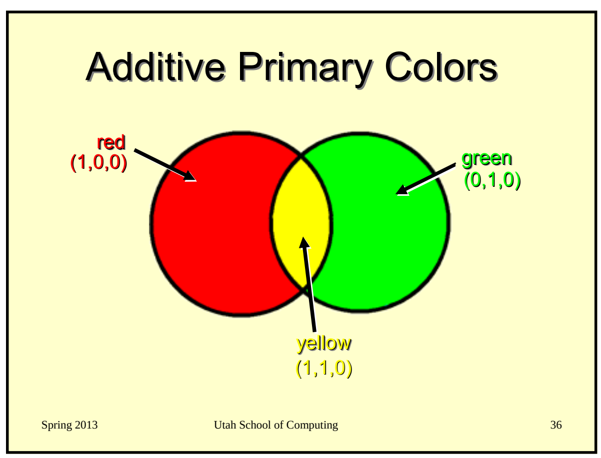
Additive Primary Colors
red
(1,0,0)
green
(0,1,0)
yellow
(1,1,0)
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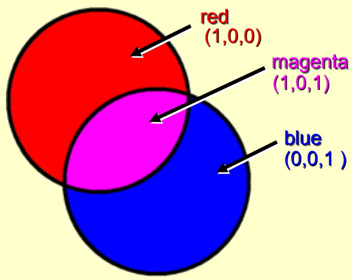
Additive Primary Colors



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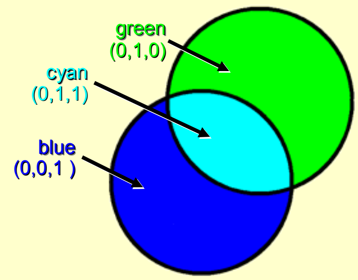
Additive Primary Colors



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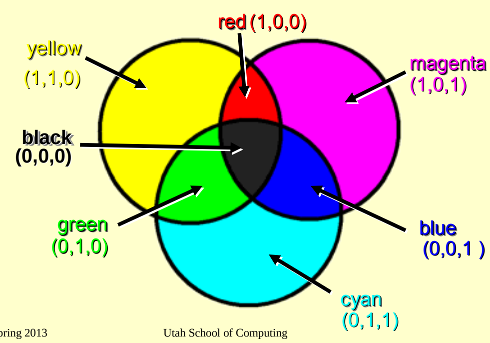
Subtractive Primary Colors



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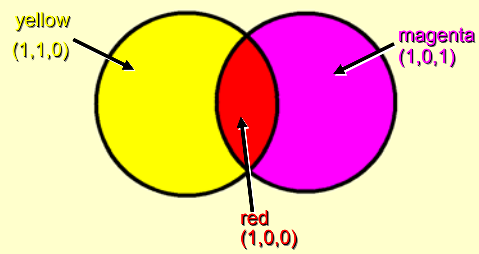
Subtractive Primary Colors



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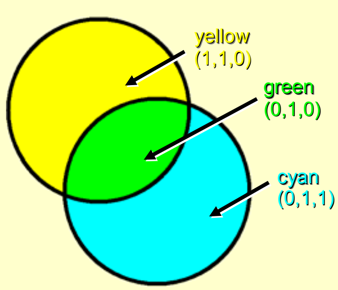
Subtractive Primary Colors



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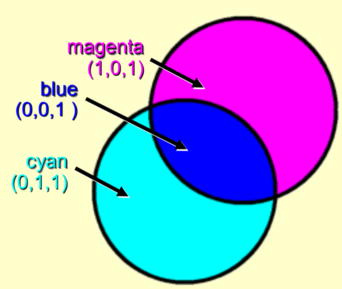
Subtractive Primary Colors



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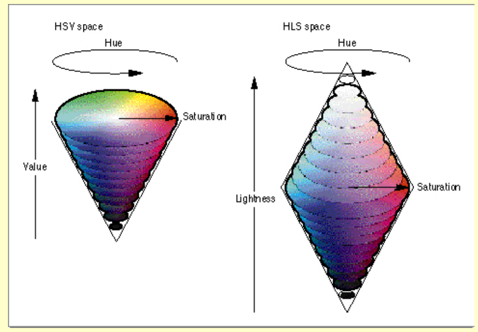
(H, S, V) *Color Space*

- Introduced by Albet Munsell, late 1800s
  - He was an artist and scientist
- Hue: Color
- Saturation/Chroma: Strength of a color
  - Neutral gray has 0 saturation
- Brightness/Value: Intensity of light emanating from image

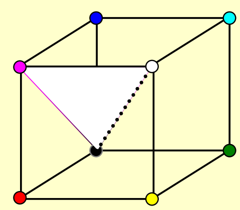
HSV/HSL



HSI/HSV

- Value/Luminance – total amount of energy
- Saturation – degree to which color is one wavelength
- Hue – dominant wavelength

Saturation



HSV

- Max = max(R, G, B)
- Min = min(R, G, B)
- S = (Max – Min)/Max
- If R==Max -> h = (G-B)/(Max-Min)
- If G==Max -> h = 2+(B-R)/(Max-Min)
- If B==Max -> h = 4 + (R-G)/(Max-Min)
- If h<0 -> H = h/6 + 1
- If h>0 -> H = h/6

HSV User Interaction

HLS

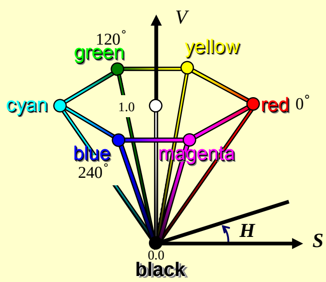
- S = sqrt(((R-G)^2 + (R-B)^2 + (G-B) ^{2})/2)
- I = (R + G + B)/3
- H = (a – arctan((R–I)b/(G-B)))/(2π) --- angle
- a =
  - –π/2 if G>B
  - –3*π/2 if G<B
  - –H = 1 if G=B
- a=sqrt(3)

(*Hue, Saturation, Value/Intensity*)

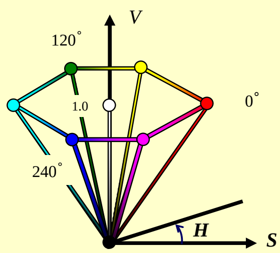
(H, S, V) *Color Space*

The *hue* of an object may be blue, but the terms *light* and *dark* distinguish the *brightness* of one object from another.

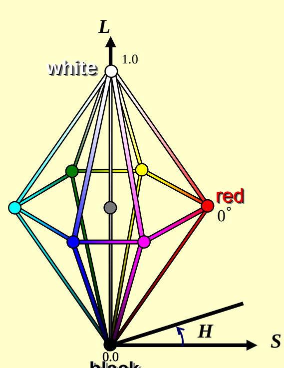
HSV Color Space (*Cone*)



HSV Color Space (*Cone*)



HLS Color Space (*double cone*)



OpenGL Color

void glColor3f (GLfloat *red* , GLfloat *green* , GLfloat *blue*);
void glColor4f (GLfloat *red* , GLfloat *green* , GLfloat *blue* , GLfloat *alpha*);

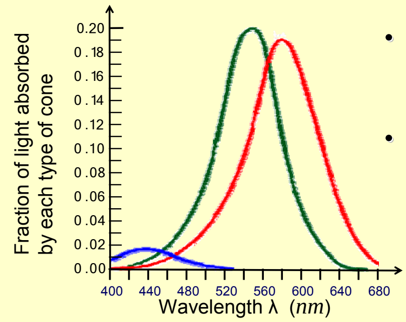
Color is OpenGL State (once set, it doesn't change)
Typical usage:

```
glBegin(GL_POINTS)
  glColor3f ( 1.0, 0.0, 0.0);
  glVertex2i ( 64, 64);
  glVertex2i (128, 128);
  glColor3f ( 0.0, 1.0, 0.0);
  glVertex2i ( 256, 256);
```

Tristimulus Color Theory

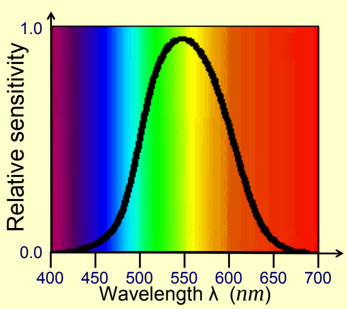
- Any color can be *matched* by a mixture of three fixed *base colors* (*primaries*)
- Eye has three kinds of color receptors called *cones*
- Eye also has *rods* (low light receptors)

Color Receptors in Eye



- Red, Green, Blue
- Long, Medium, Short

Color Receptors in Eye



CIE Color Space*

(X, Y, Z) represents an imaginary basis that does not correspond to what we see

Define the *normalized coordinates*:

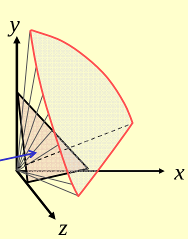
$x = X / (X + Y + Z)$
$y = Y / (X + Y + Z)$
$z = Z / (X + Y + Z)$

* Commission Internationale de l'Êclairage

CIE Color Space of Visible Colors

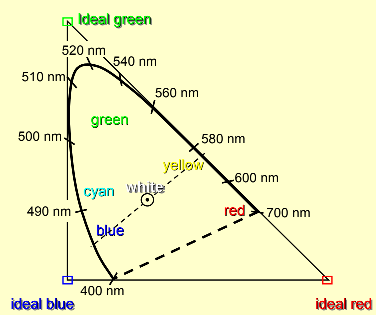
$x = X / (X + Y + Z)$
$y = Y / (X + Y + Z)$
$z = Z / (X + Y + Z)$

$x + y + z = 1$

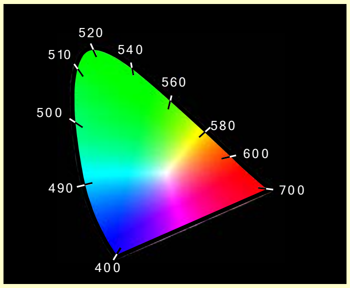


The projection of the plane of the triangle onto the (X,Y) plane forms the chromaticity diagram that follows.

Color Gamuts: *CIE Color Chart*

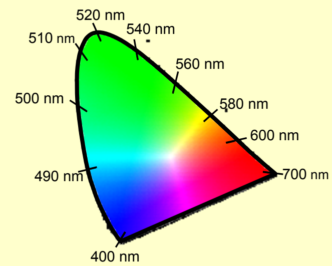


Color Gamuts: *CIE Color Chart*



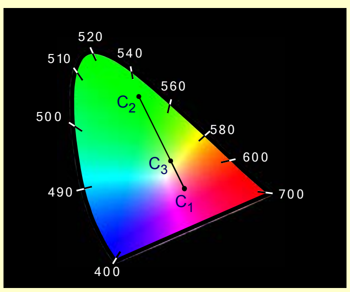
www.cs.rit.edu/~ncs/color/a_chroma.html

Color Gamuts: *CIE Color Chart*



www.cs.rit.edu/~ncs/color/a_chroma.html

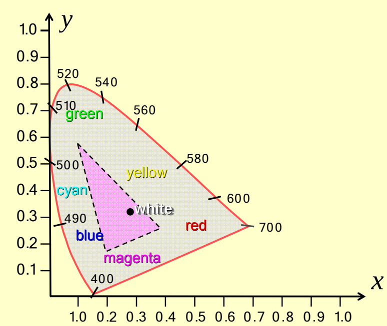
Color Gamuts: *CIE Color Chart*



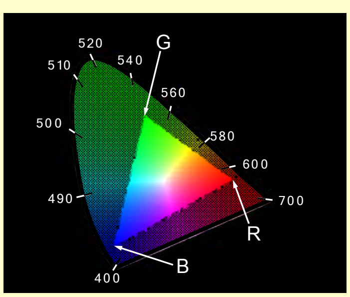
The additive colors C_1 and C_2 combine to form C_3 on the line connecting C_1 and C_2.

www.cs.rit.edu/~ncs/color/a_chroma.html

Color Gamuts: *CIE Color Chart*



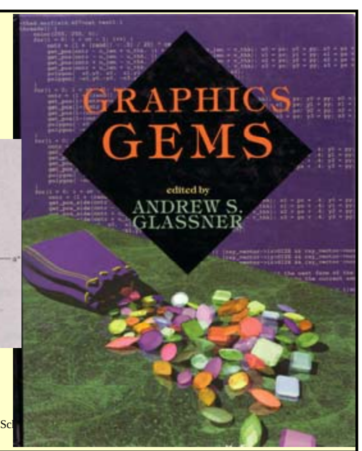
Color Gamuts: *CIE Color Chart*



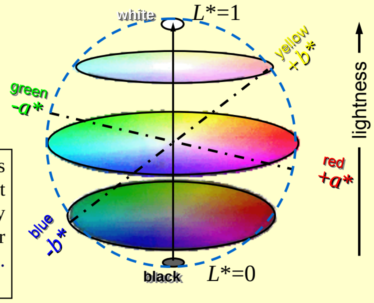
The Color Gamuts of different displays and printers are not likely to match. Printers usually have smaller gamuts.

www.cs.rit.edu/~ncs/color/a_chroma.html

Gamuts



*CIE L*a*b** Color Space

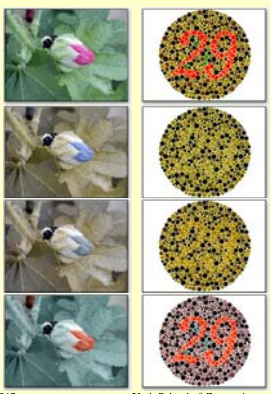


Equal distances represent approximately equal color difference.

Trichromatic Theory Shortcomings

- Color blindness
  - –R-G, B-Y, All
- Yellow seems primary
- Color constancy

Color Blindness



Normal

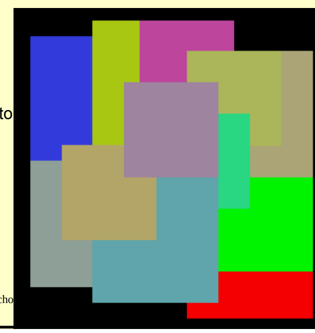
Protan (L-cone)

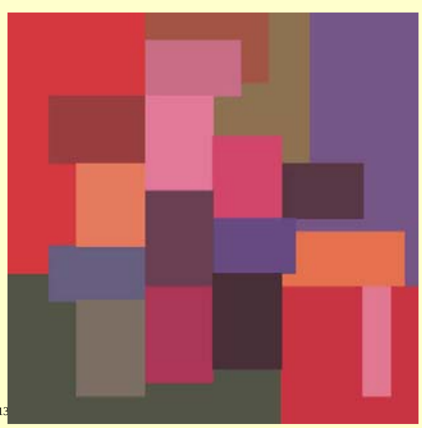
Deutan (M-cone)

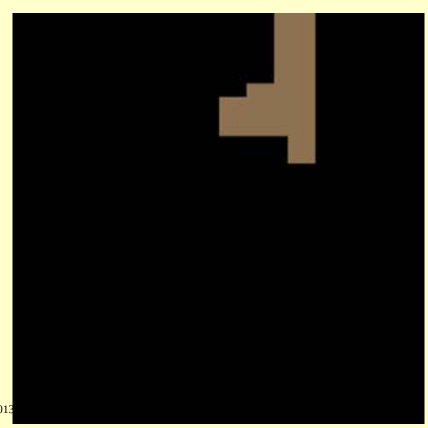
Tritan (S-cone)

Mondrian Color Patches

- Colors look different depending on their neighbors
- Adjacency/black lines
- Color edges are critical to color perception
- Can determine color in non-white lighting conditions

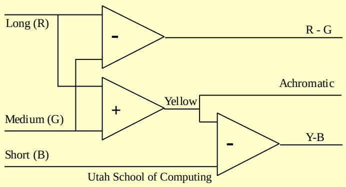






Opponent Color Theory

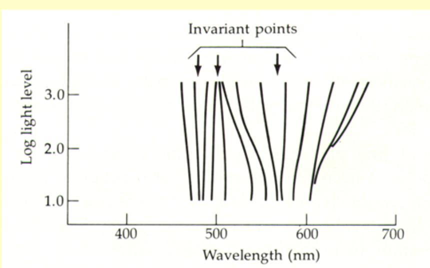
- Humans encode colors by differences
- E.g R-G, and B-Y Differences
  - Color blindness



Perceptual Distortions

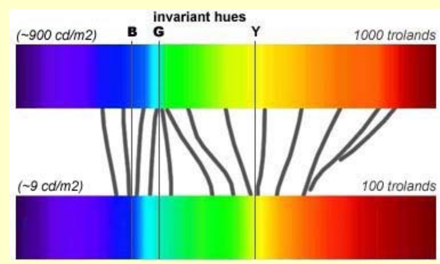
- Color-deficiency
- Interactions between color components
  - brightness - hue (Bezold-Brucke Phenomenon)
  - saturation - brightness (Helmholtz-Kohlrausch effect)
- Simultaneous contrast
  - brightness
  - hue
- Small field achrominance
- Effects of color on perceived size

Bezold-Brucke Phenomenon



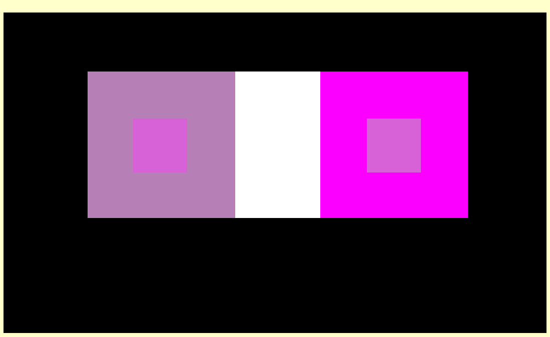
- Hurvich '81, pg. 73.

Bezold-Brucke Phenomenon

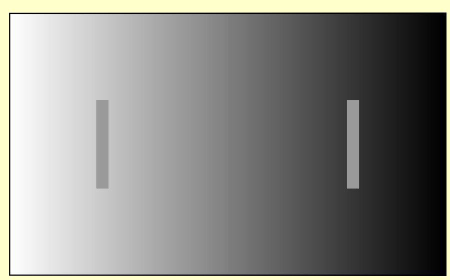


- Hurvich '81, pg. 73.

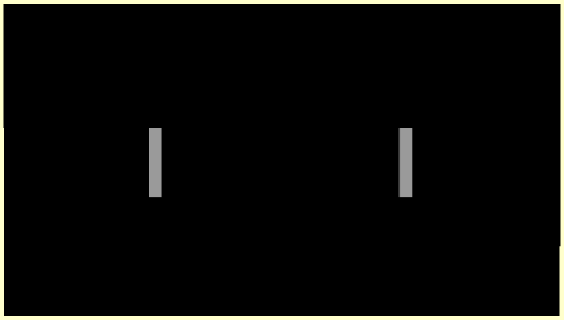
Helmholtz-Kohlrausch effect



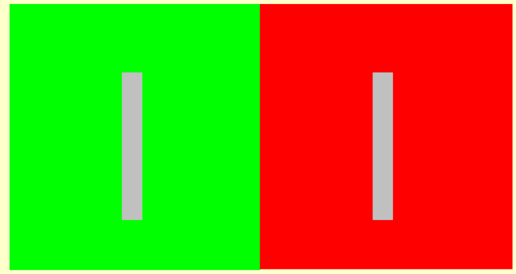
Simultaneous Contrast



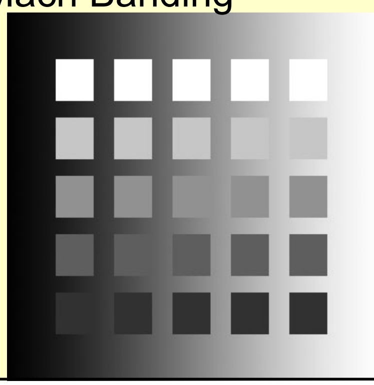
Simultaneous Contrast

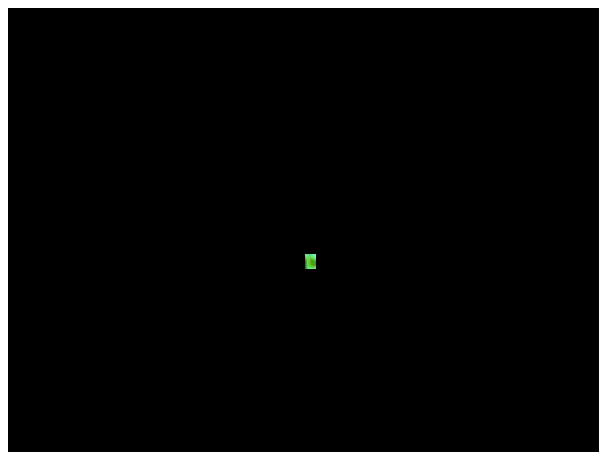


Simultaneous Contrast

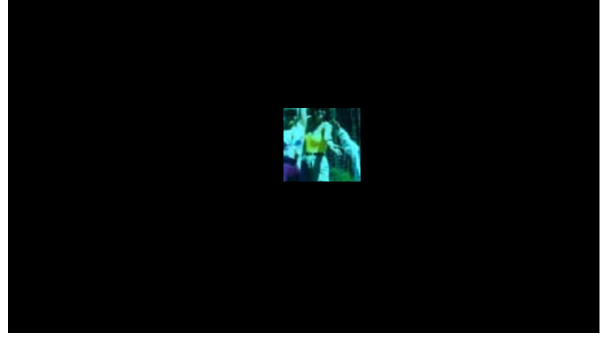


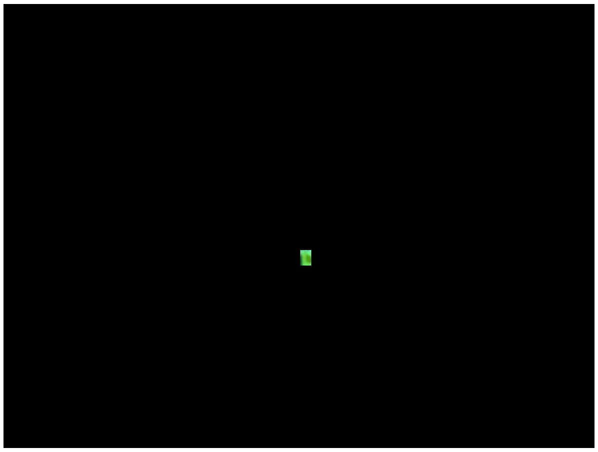
Mach Banding





Chromatic Adaptation





Color Applets

www.cs.brown.edu/exploratories/freeSoftware/repository/edu/brown/cs/exploratories/applets/combinedColorMixing/combined_color_mixing_java_browser.html

Lecture Set 1

End Color