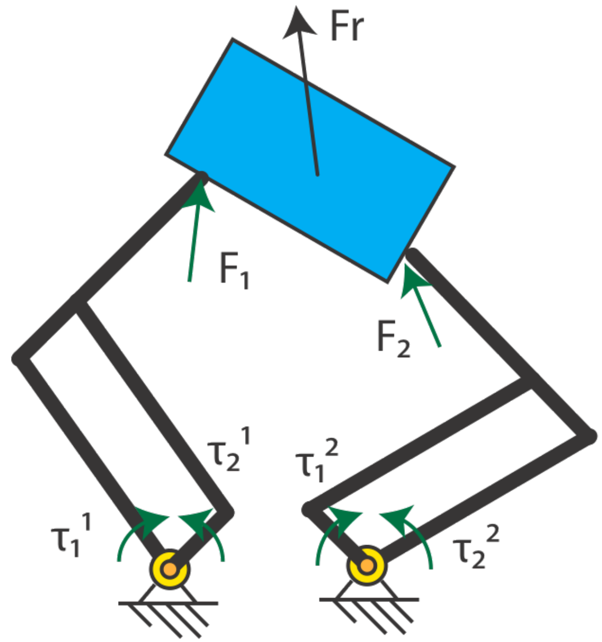
Seeing with new eyes

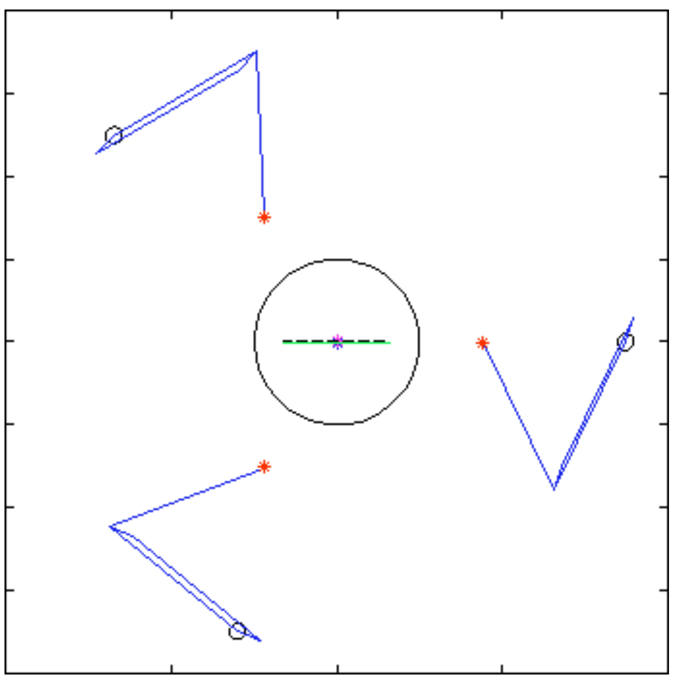
Applied science of color theory, perception, projections, shapes, and compositing

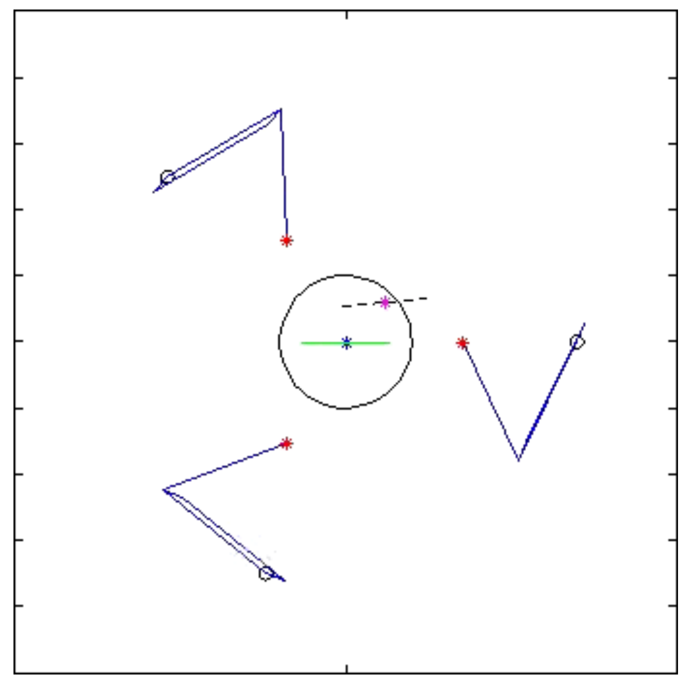
Alex Simpkins, Ph.D.

About what I do

- Control theory
  - Models of human movement and learning
  - Manipulation and locomotion

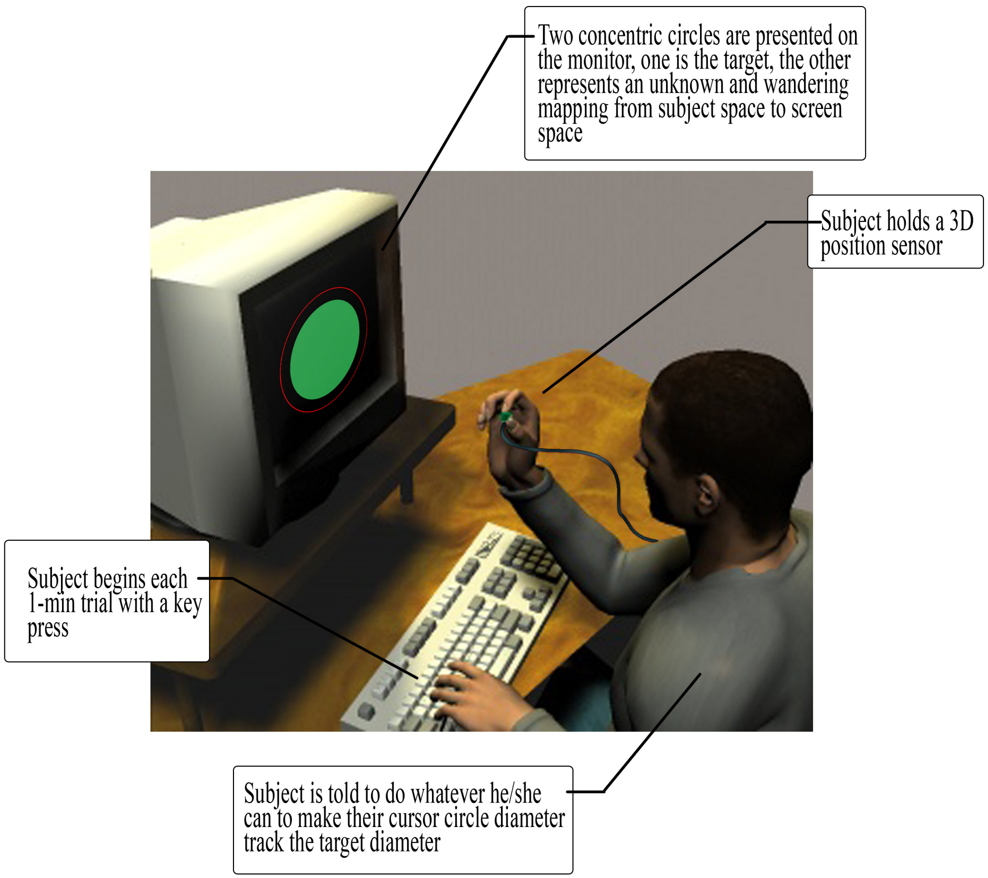






About me

- Learning
  - Active learning



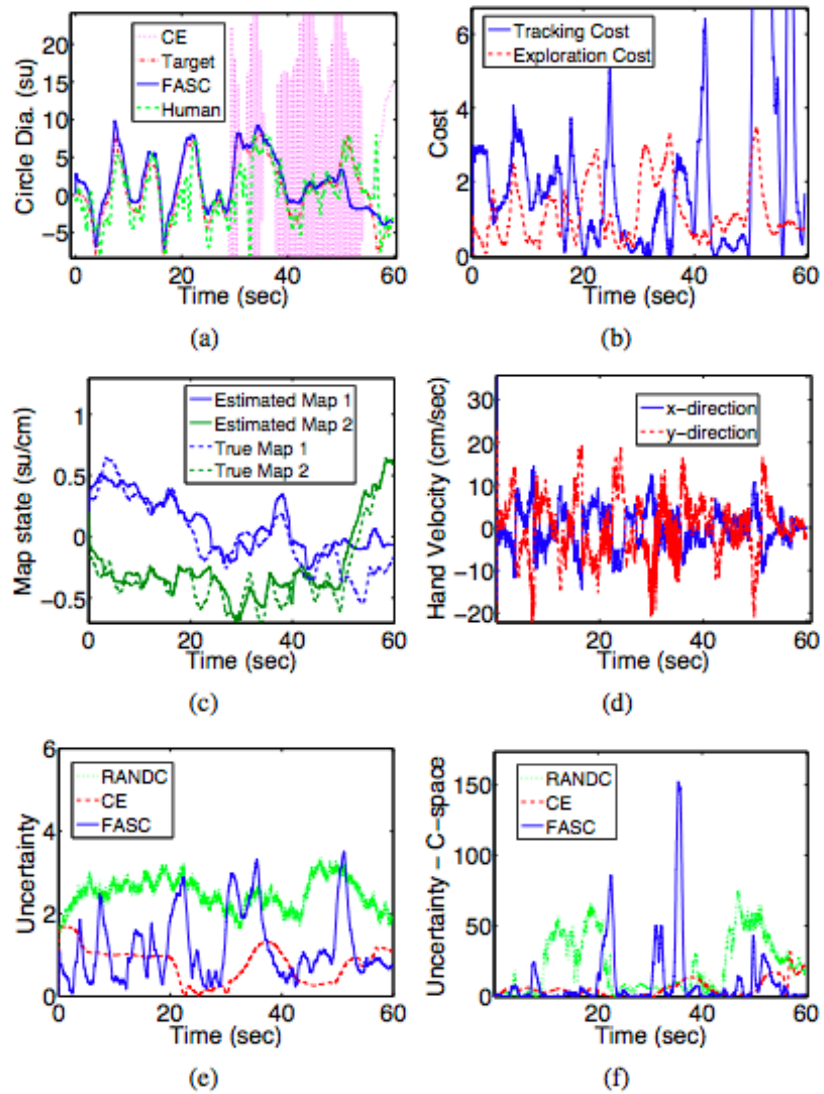
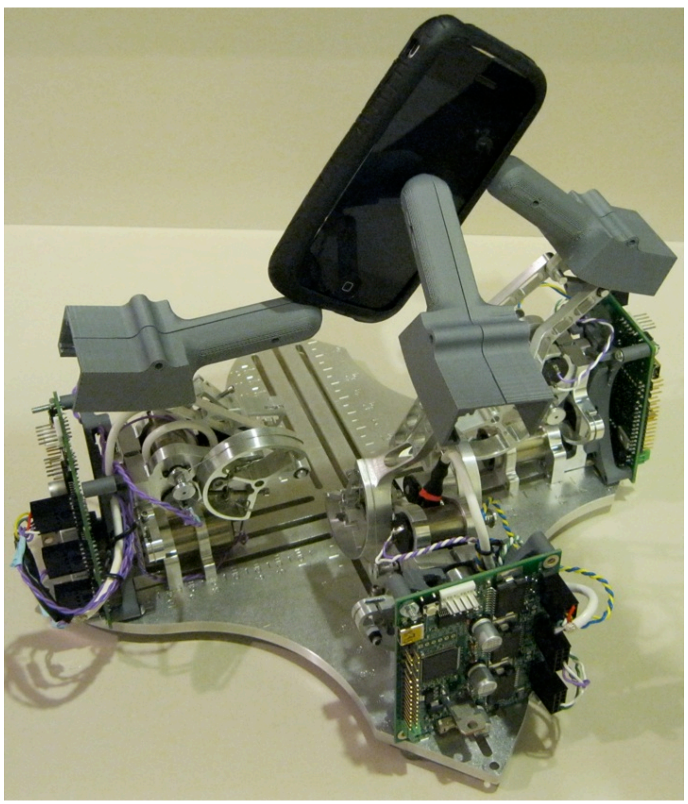


Fig. 2. (a) A section of a 60 second trial displaying human subject data, FAS, and proportional feedback controller tracking. (b) represents the two portions of the cost - the tracking and exploration costs. Plot (c) shows the true and estimated map. (d) shows the FAS control actions. (e) and (f) show two measures of uncertainty - (e) is in h-space, and is given by the trace term in 12, while (f) is the same, but in $h^{\perp}$-space.

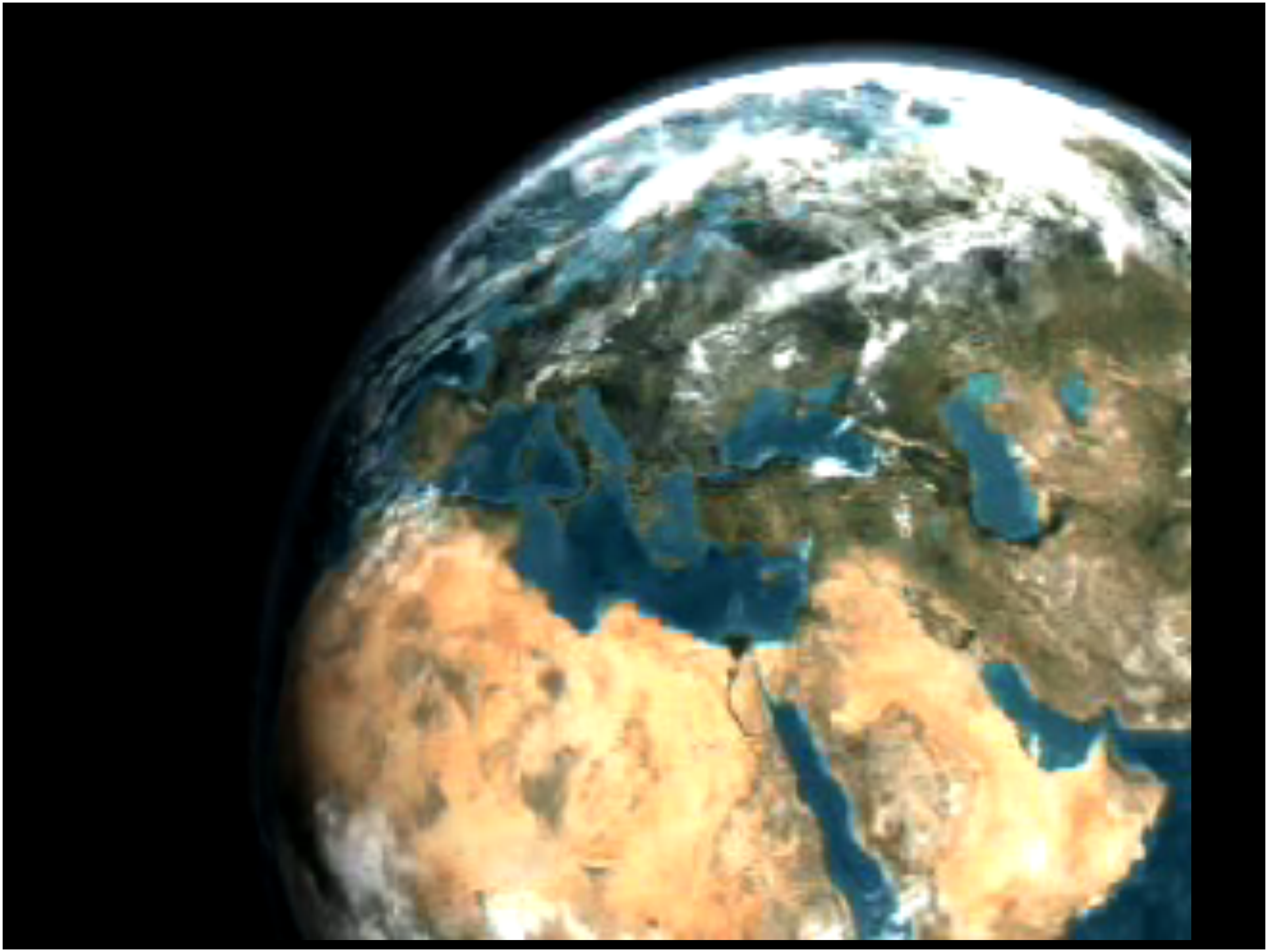
About me

- Robotics
  - Design and control
- Learning/AI
- Design



Why study perception and color theory?

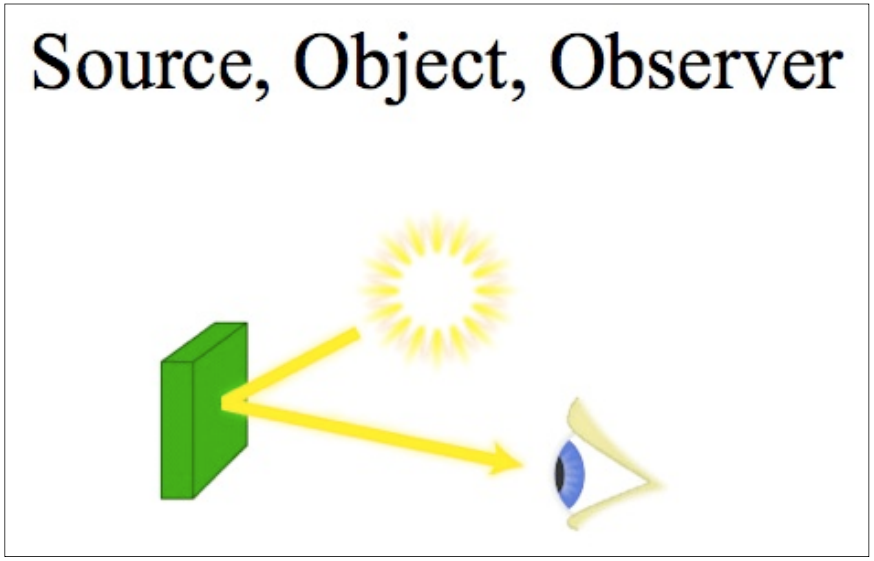
- Human brain has trouble making sense of large amounts of data
  - Brain uses strategies, you can play on those
- By understanding how perception works, you can enhance your ability to produce effects in the viewer's brain
  - Art is in the viewer
- Scientific visualization is one way of making important information explicit and simple to process



Visualization

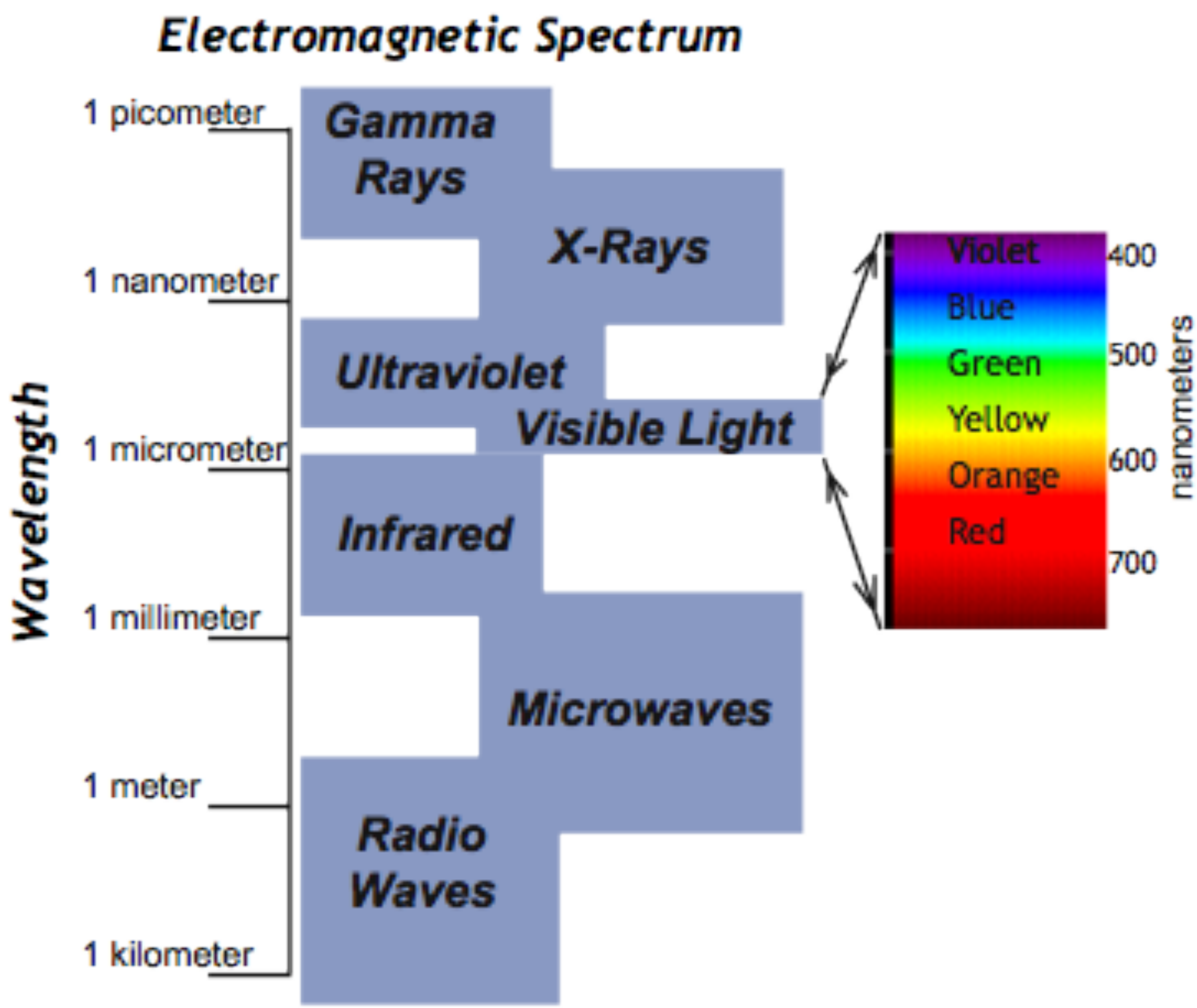
- Can communicate information without words, by encoding motion as part of the information
- http://svs.gsfc.nasa.gov/

What is color?

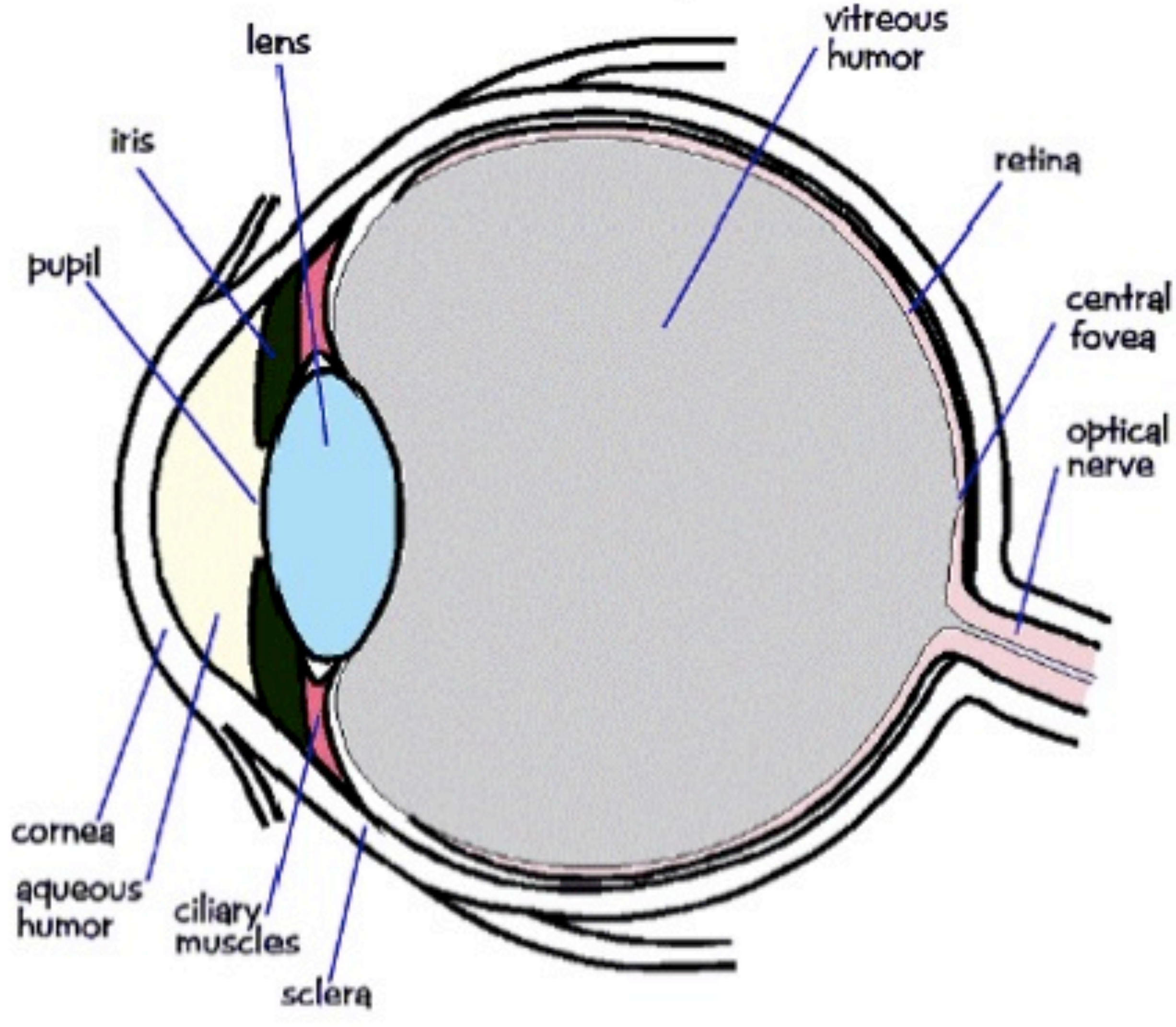


- Reflected light = color of object
- Color is the set of wavelengths of light reflected from an object
- A light source can be a light bulb, the sun, etc or another object

Electromagnetic Spectrum



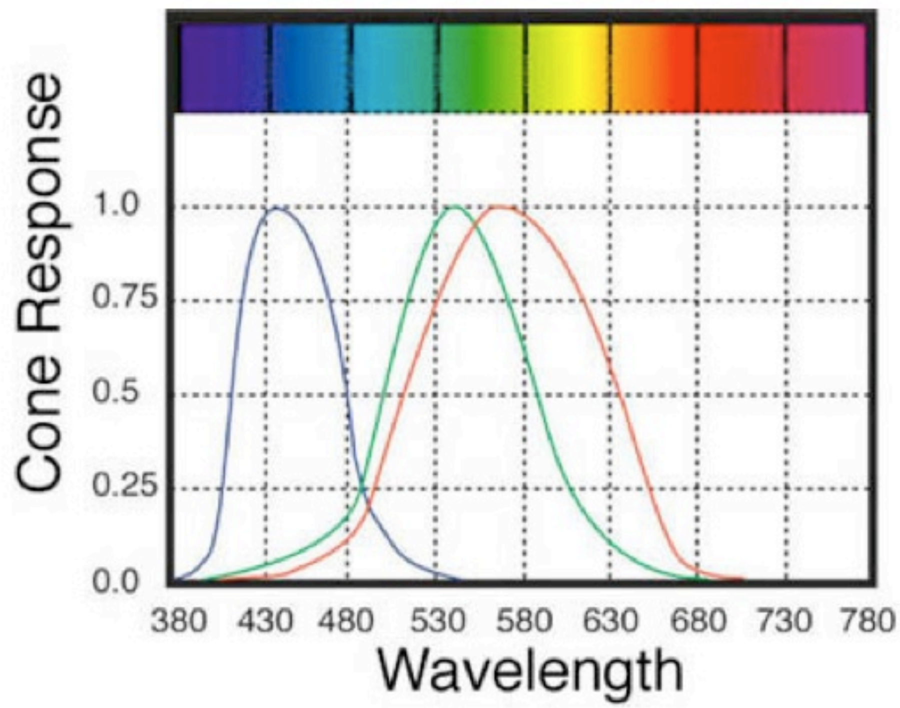
The Eye



lens
vitreous humor
iris
retina
pupil
central fovea
optical nerve
cornea
aqueous humor
ciliary muscles
sclera

Rods and Cones

- **Rods** - sensitive to intensity (black and white sensitivity in low light conditions)
- **Cones** - three types, S, M and L corresponding to short, medium and long wavelength light sensitivities

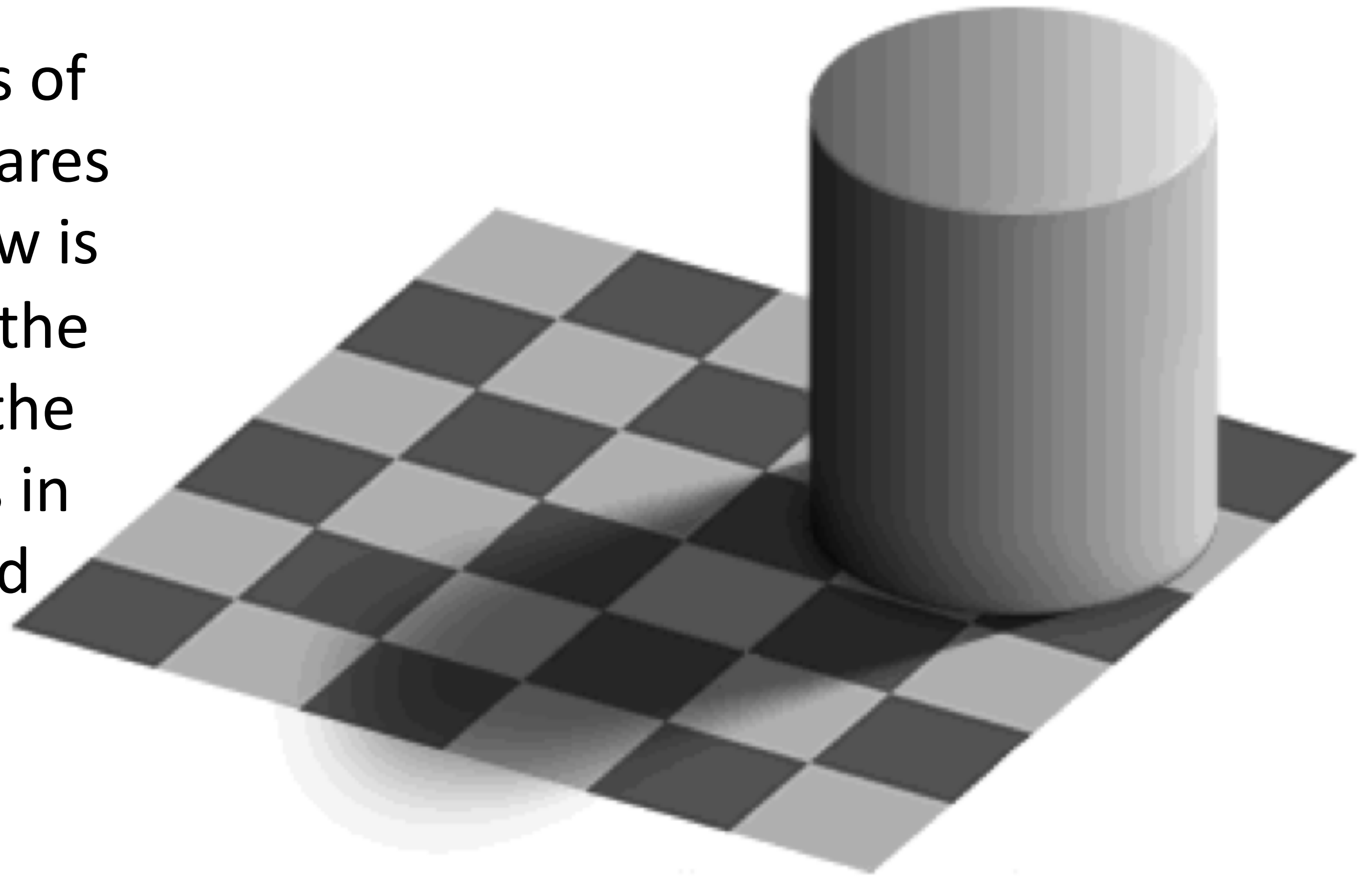


Human perception of color

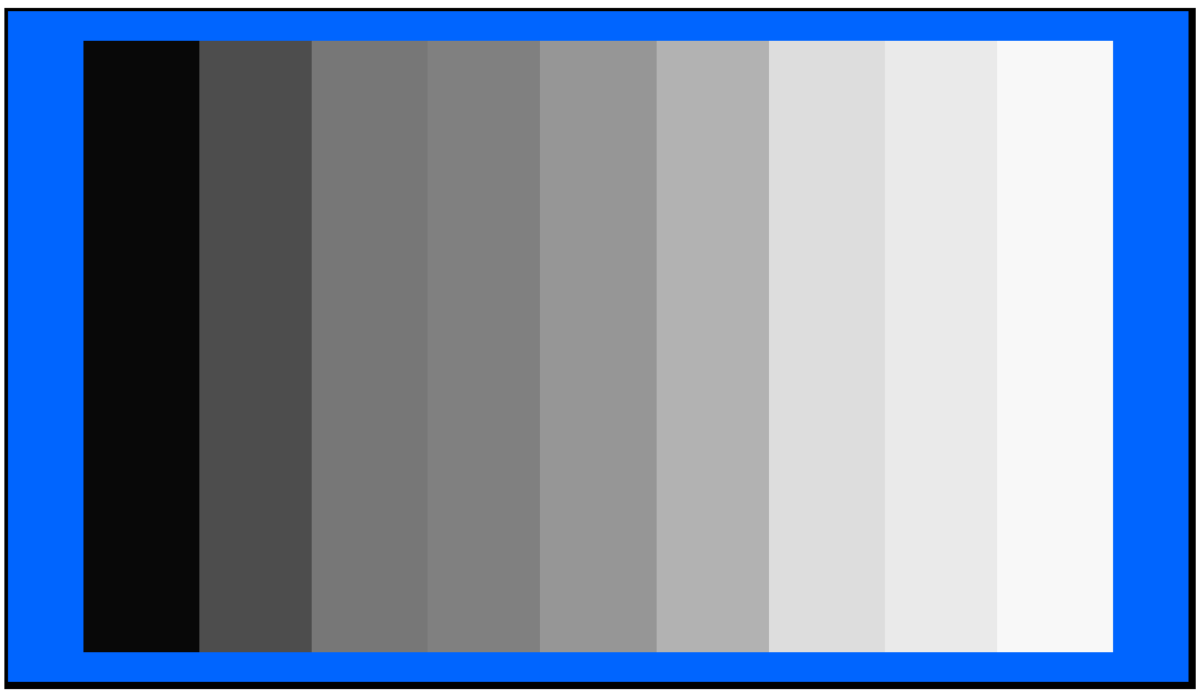
- Color constancy - our visual perception is constantly adjusting to compensate for changing surroundings
- Human color perception is context dependent
  - Ever try to perceive the difference between two colors of clothing in low light?
  - Movie example - Abyss Yellow/green light source, “Cut the blue wire with the white stripe, NOT the black wire with the yellow strip”
    - Side note- how to fix this as the designer of the device? Use one wire with dashes instead of a stripe - “Cut the wire with the dashes.” Person cutting: “Easy. It’s done!”

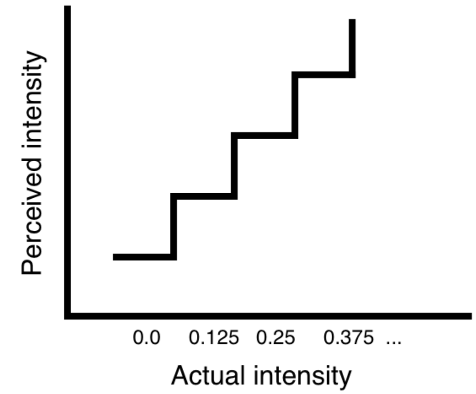
Perceived lightness is context-dependent as well

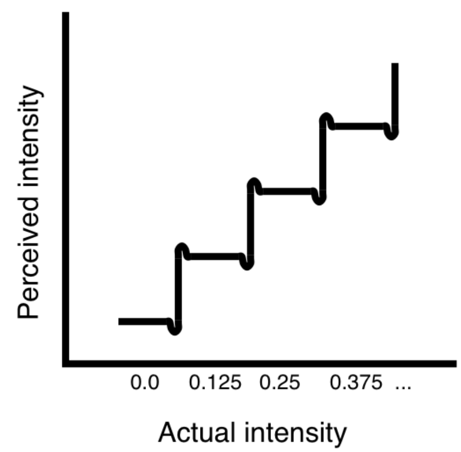
- The lightness of the light squares in the shadow is the same as the lightness of the dark squares in the unshaded region



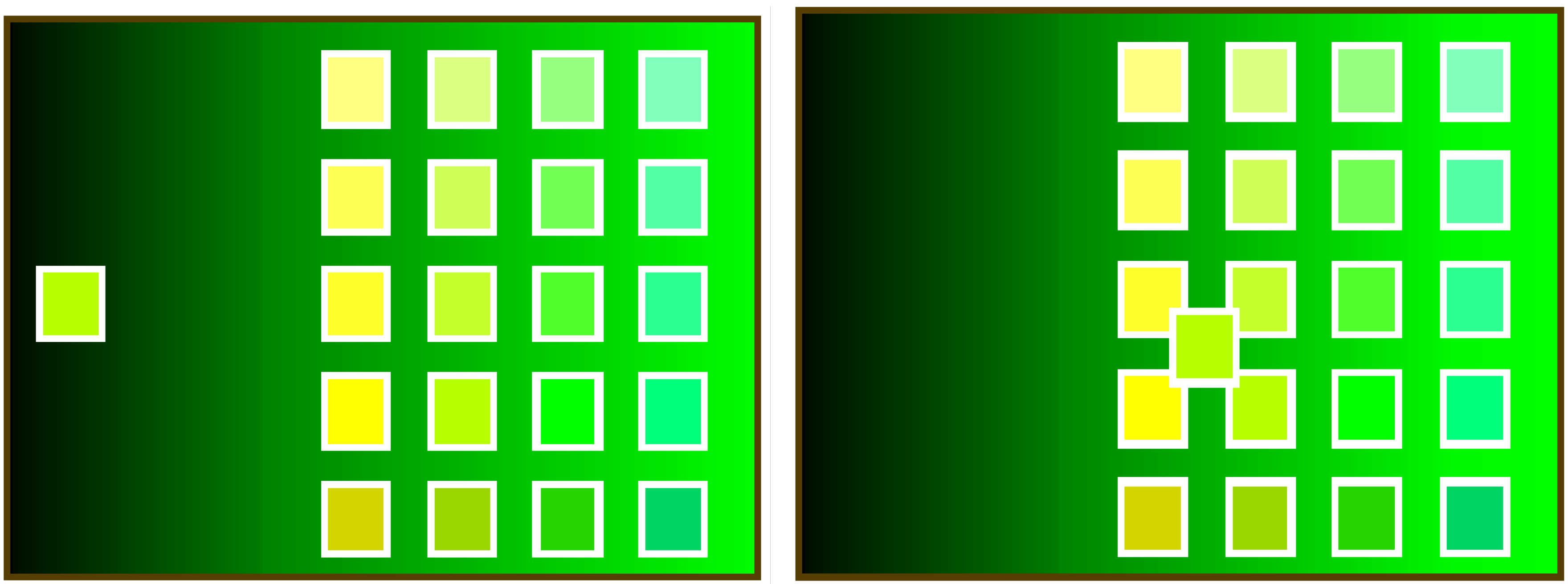
Beware of Mach Banding



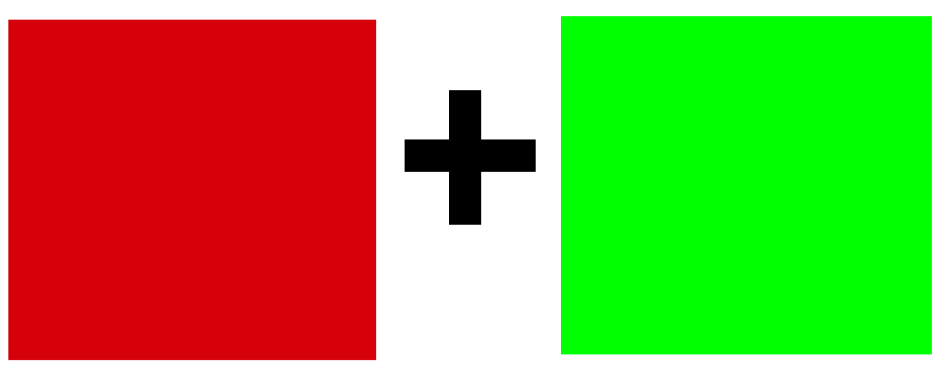




Recall that perceived color intensity is also context-dependent



Perceptual example: Afterimages



Perceptual example: Afterimages

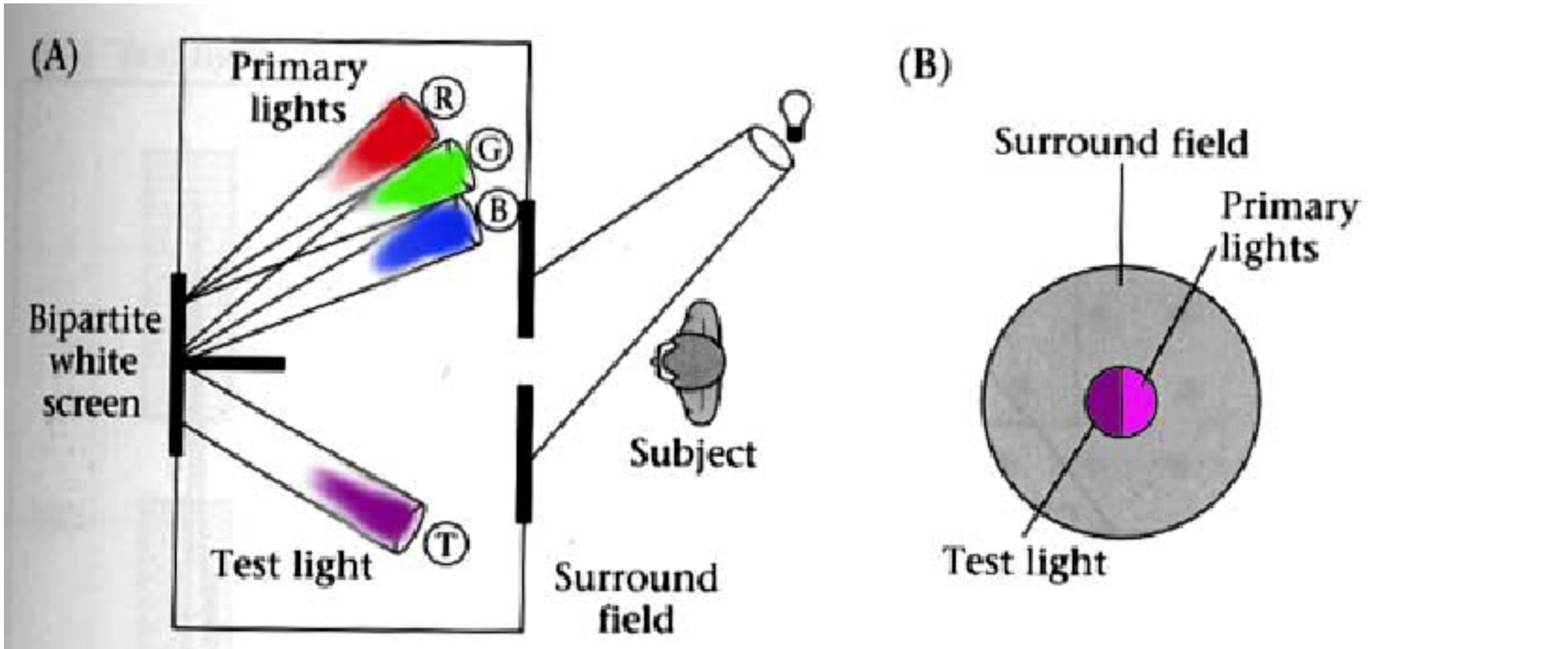
Blindness test

- http://www.youtube.com/watch?v=0grANlx7y2E

So on the one hand…

- Can color be quantified ?
- Can a color be uniquely defined ?
- Is there a “common understanding” about colors ?

CIE Color Matching Experiment



4.10 THE COLOR-MATCHING EXPERIMENT. The observer views a bipartite field and adjusts the intensities of the three primary lights to match the appearance of the test light. (A) A top view of the experimental apparatus. (B) The appearance of the stimuli to the observer. After Judd and Wyszecki, 1975.

Basis for industrial color standards and "pointwise" color models.

Color Matching Experiment

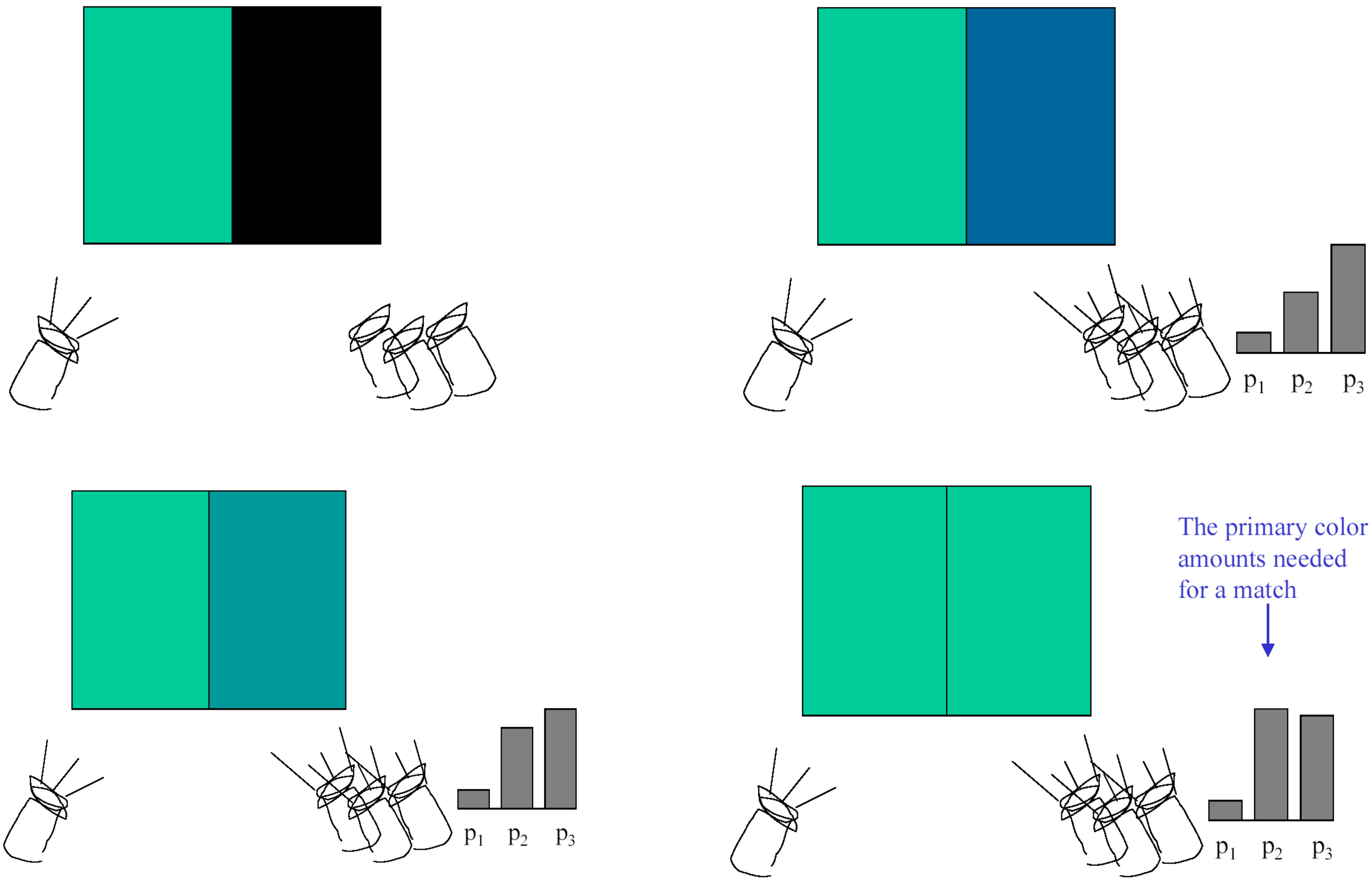
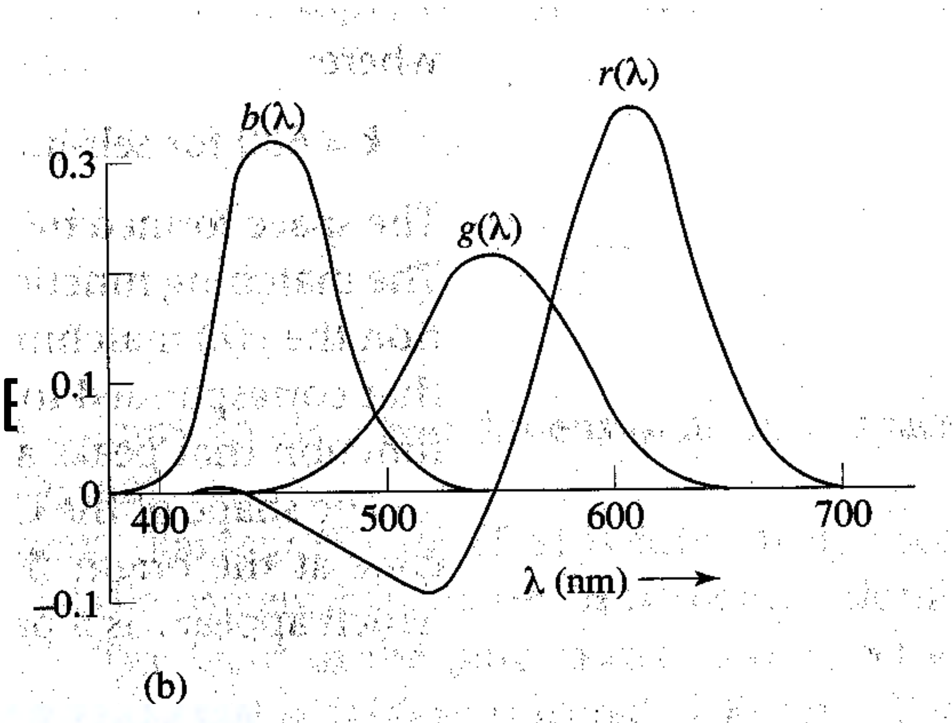


Image courtesy Bill Freeman

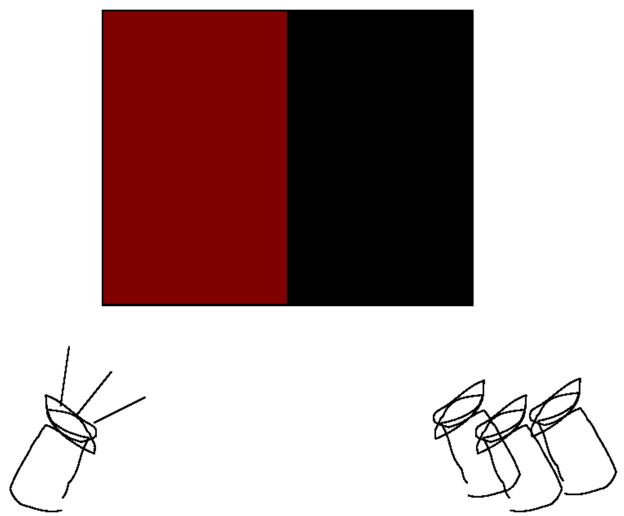
CIE Experiment Result

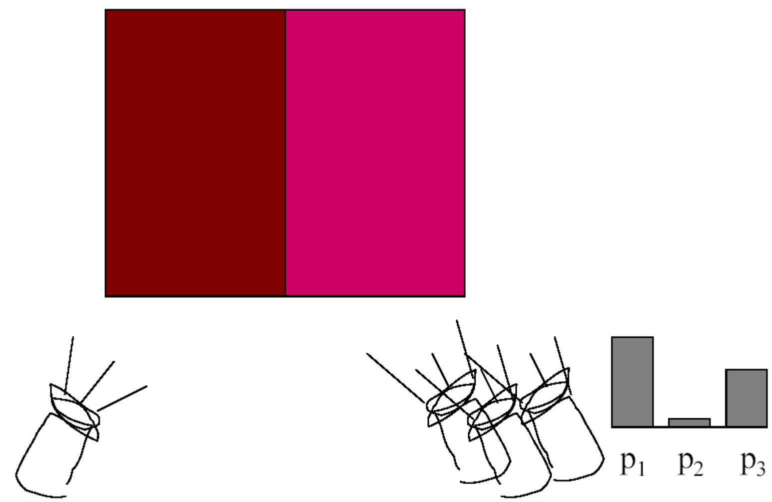
- Three pure light source: R = 700.0 nm, G = 546.1 nm, B = 435.8 nm.

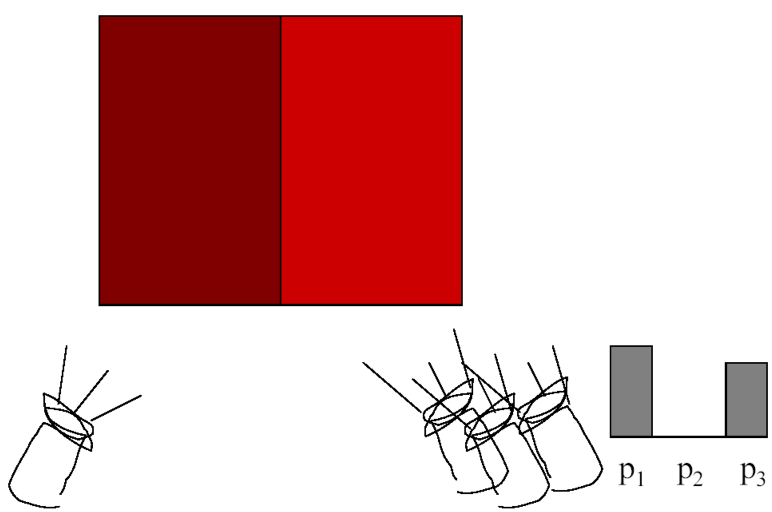


$$C_\lambda = r(\lambda) + g(\lambda) + b(\lambda)$$

Color Matching Experiment

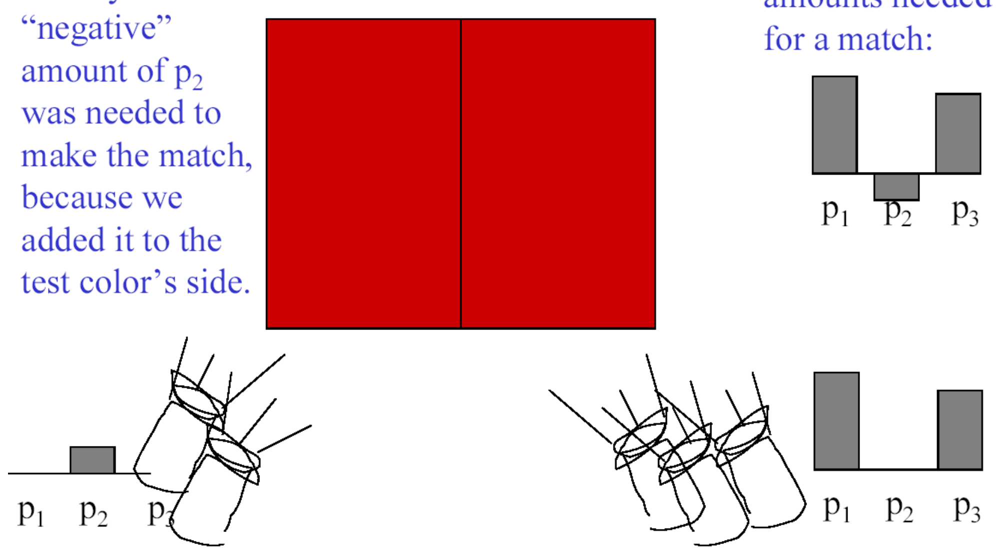






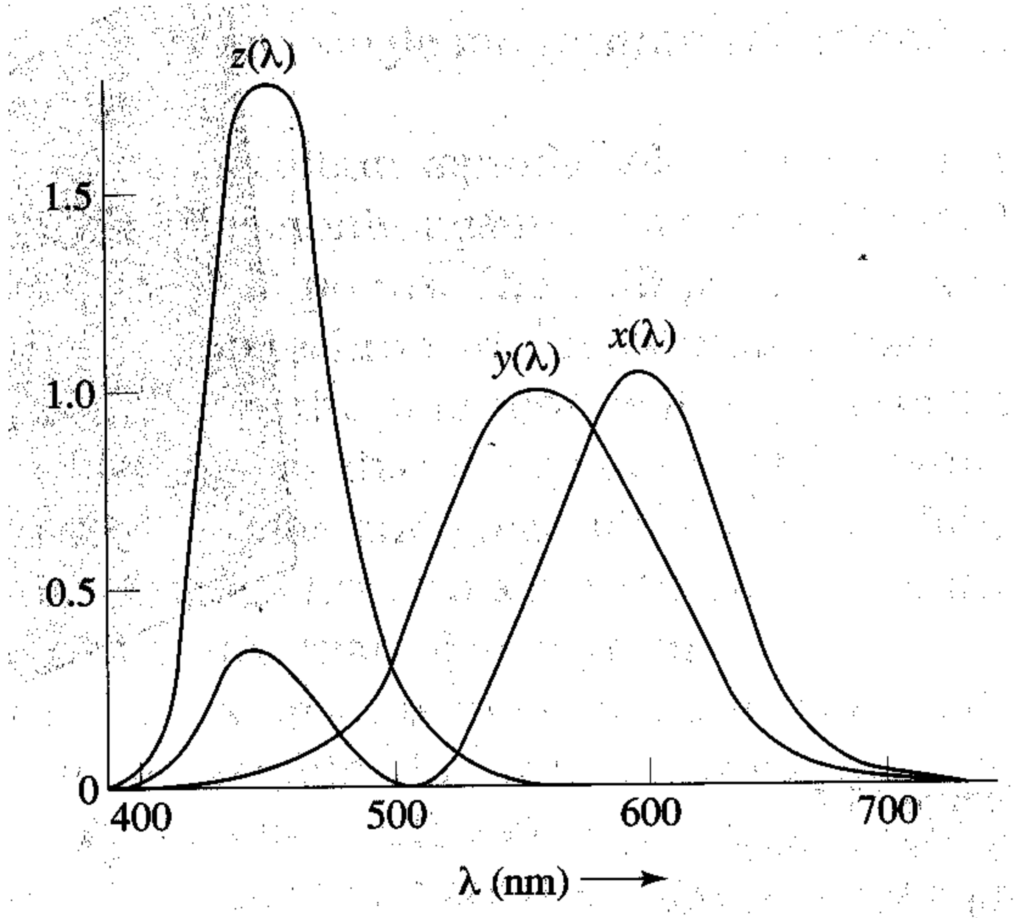
We say a "negative" amount of p_2 was needed to make the match, because we added it to the test color's side.

The primary color amounts needed for a match:

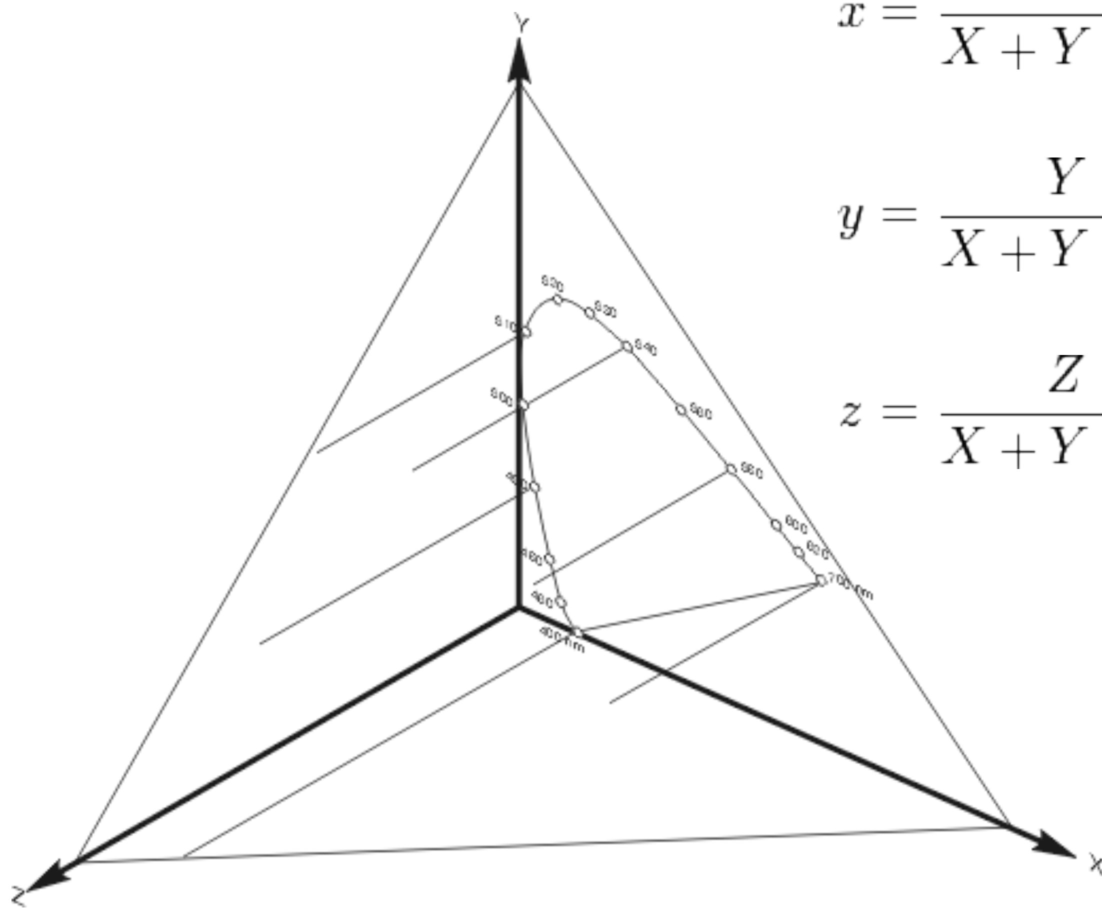


CIE Color Space

- 3 hypothetical light sources, X, Y, and Z, which yield positive (why?) matching curves
- Y: roughly corresponds to luminous efficiency characteristic of human eye



3D Tri-chromatic Space

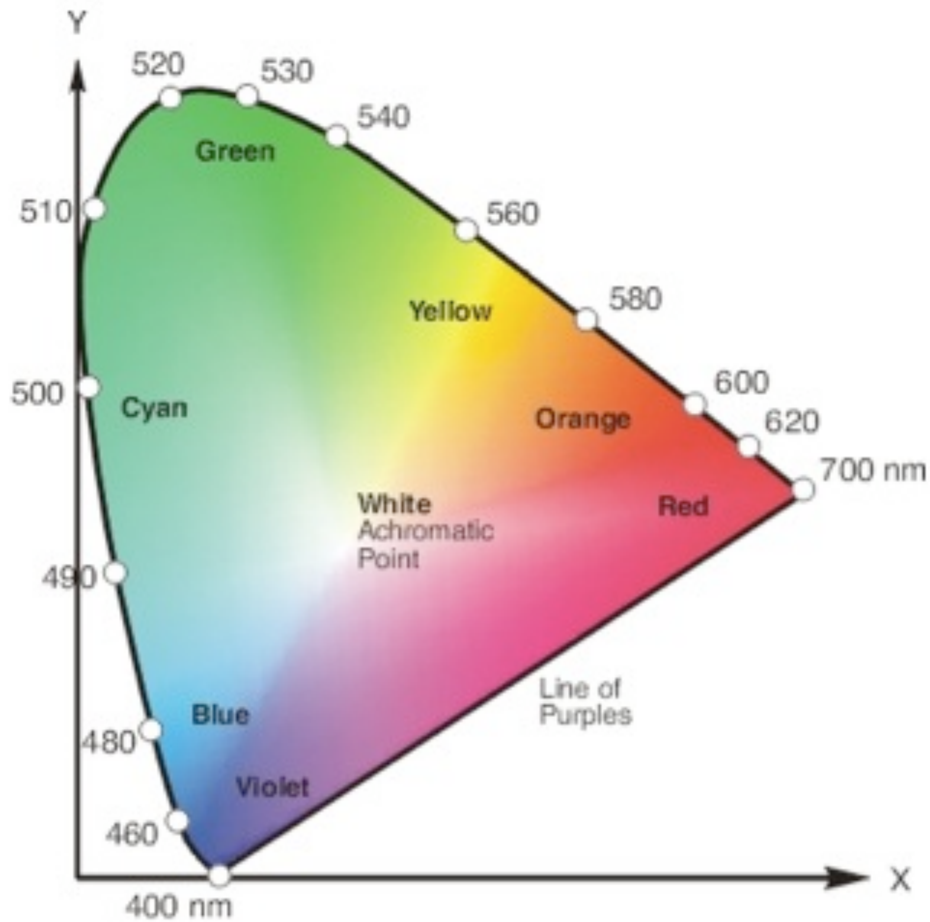


$$x = \frac{X}{X+Y+Z}$$

$$y = \frac{Y}{X+Y+Z}$$

$$z = \frac{Z}{X+Y+Z} = 1 - x - y$$

CIE Color chromaticity chart (CIExyY)

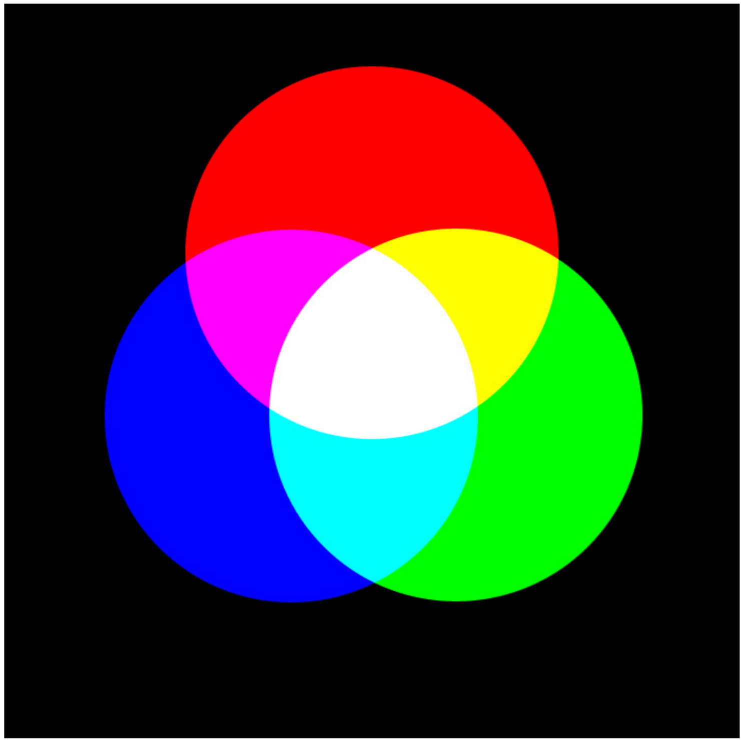


Color spaces

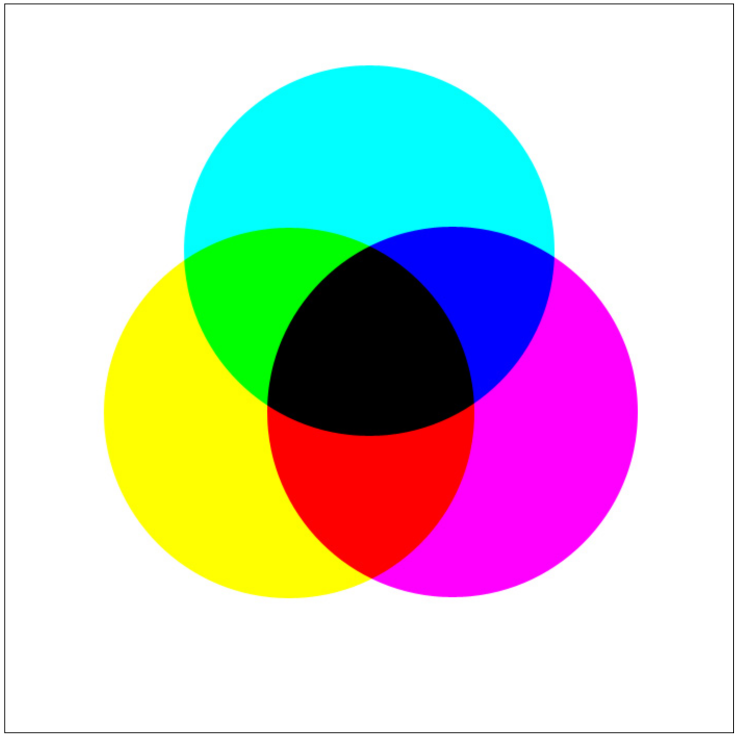
- Now that we have a sense of how we perceive light and color, we can define several *MODELS* of color
- Each color is assigned a coordinate which has three components relative to some color *space model (*ie RGB)
- Some of these color spaces are additive, some are subtractive
- This ultimately is what allows us to make devices that produce color

Additive vs. subtractive color

Additive (RGB)



Subtractive (CMY)



$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1-R \\ 1-G \\ 1-B \end{bmatrix}$$

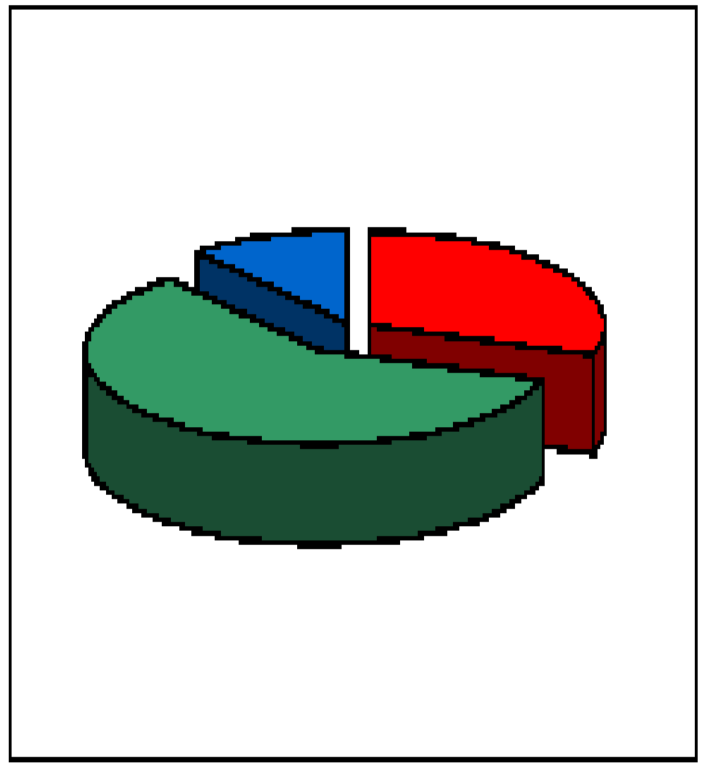
Color models

- RGB
  - red-green-blue
  - Additive scheme
- CMY
  - Cyan-magenta-yellow
  - Subtractive scheme
  - Black (CMYK) is typically added to inkjet printers
    - Difficult to make exact black by mixing CMY, requires precision
    - Typically one uses black the most so it makes sense to have a separate ink cartridge for black
- HSV
  - Hue-saturation-value
  - Many feel this is a more natural way to describe color for humans

Luminance equation reviewed

- Perceived intensity due to a color
  - **Different contributions of red/green/blue components**
  - **Empirically determined**

$$Y = .30*Red + .59*Green + .11*Blue$$



≈ Contrast Table

	Black	White	Red	Green	Blue	Cyan	Magenta	Orange	Yellow
Black	0.00	1.00	0.30	0.59	0.11	0.70	0.41	0.60	0.89
White	1.00	0.00	0.70	0.41	0.89	0.30	0.59	0.41	0.11
Red	0.30	0.70	0.00	0.29	0.19	0.40	0.11	0.30	0.59
Green	0.59	0.41	0.29	0.00	0.48	0.11	0.18	0.01	0.30
Blue	0.11	0.89	0.19	0.48	0.00	0.59	0.30	0.49	0.78
Cyan	0.70	0.30	0.40	0.11	0.59	0.00	0.29	0.11	0.19
Magenta	0.41	0.59	0.11	0.18	0.30	0.29	0.00	0.19	0.48
Orange	0.60	0.41	0.30	0.01	0.49	0.11	0.19	0.00	0.30
Yellow	0.89	0.11	0.59	0.30	0.78	0.19	0.48	0.30	0.00

Example: Bad color matching

- Eeeghh!
- The red and blue are on opposite ends of the visual color spectrum, so we have trouble focusing on both colors simultaneously
- I could have made this worse by adding all equations, but last time too many people passed out!
- AVOID REDS ON BLUES OR BLUES ON REDS

Example: Good color matching

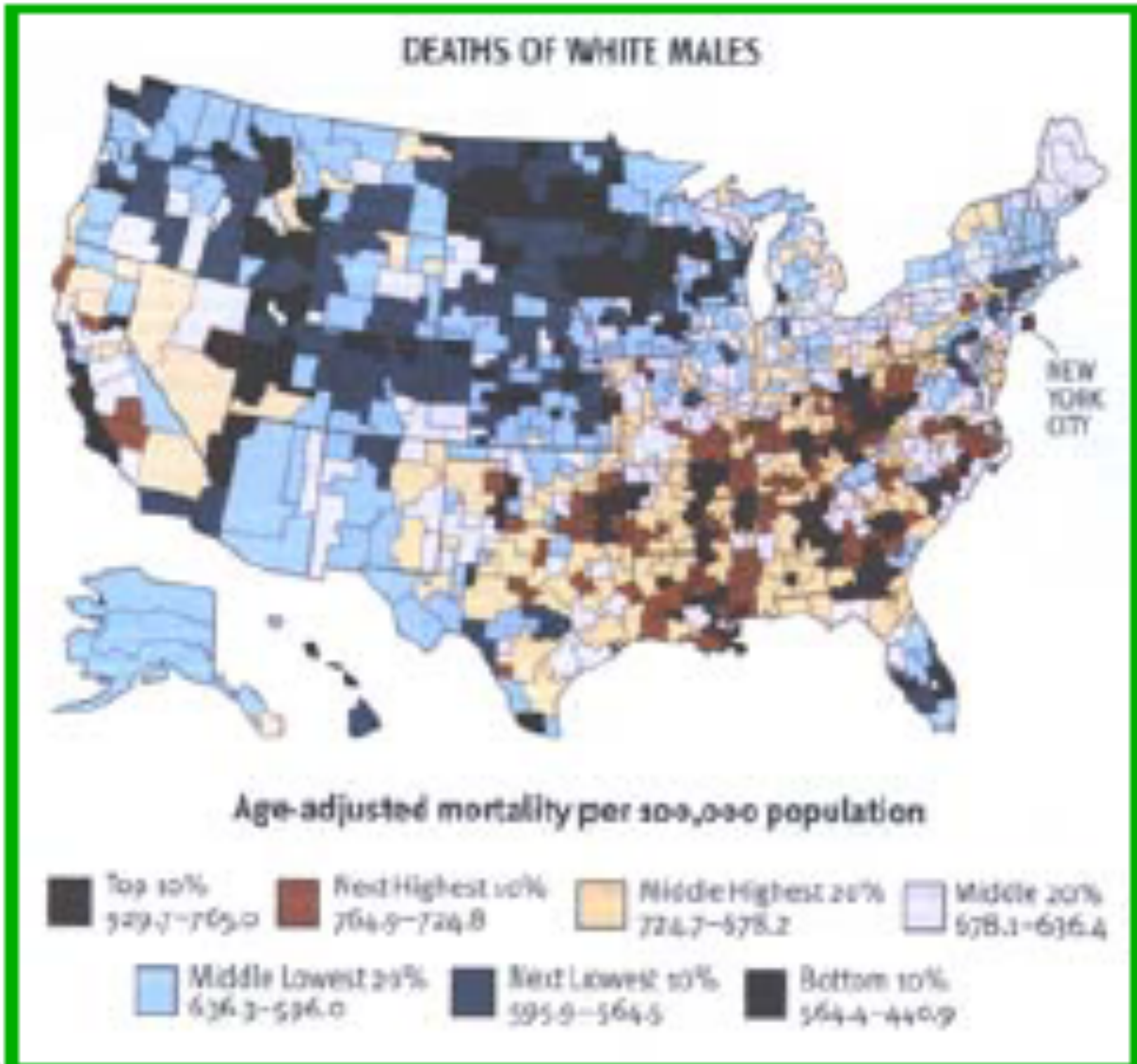
- Ahhh…
- This is much more comfortable for the eyes.
- Choose colors which are based on luminance differences
- generally avoid two fully saturated colors as foreground and background
- Increase contrast by reducing the perceived intensity of either the foreground or background

Bad Contrast

Bad Contrast
Bad Contrast

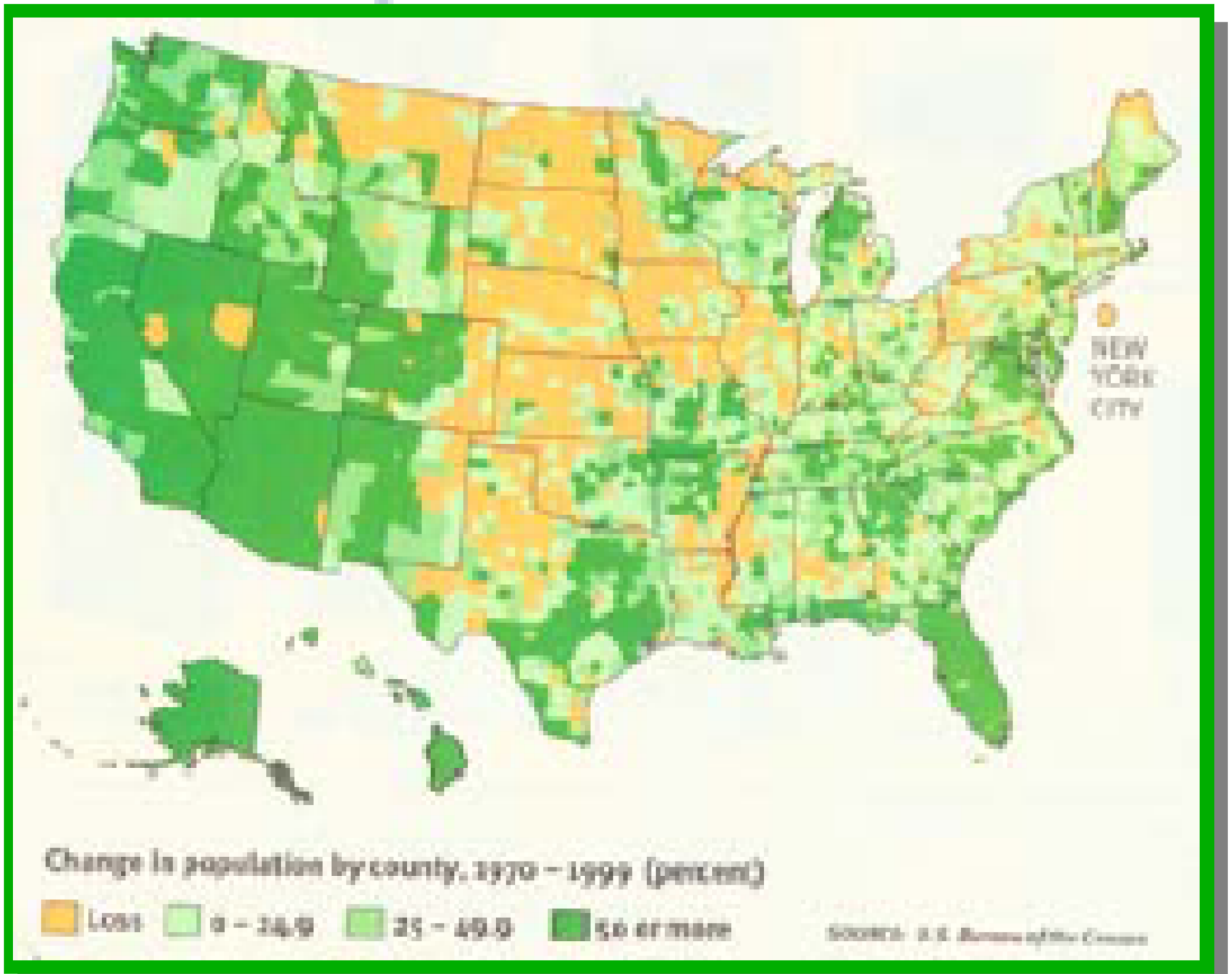
- The most important thing you need to know to get the most out of your education is that you should value the learning and try to make it your own
- The most important thing in this paper is that we did not really find anything important

What's Wrong with this Picture?



Source:
Scientific American,
June 2000

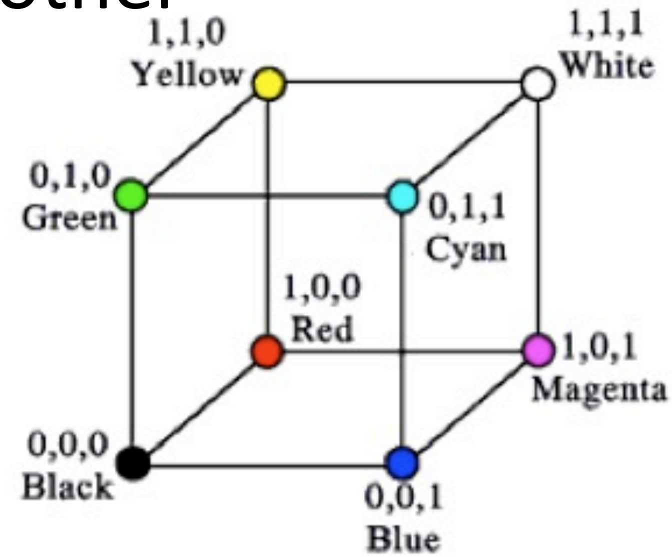
What's Right with this Picture?

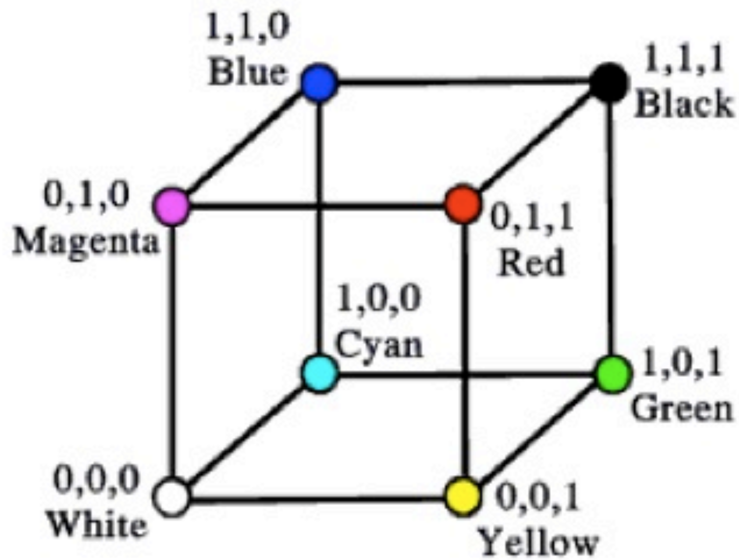


Source:
Scientific American,
August 2000

RGB and CMY color cubes

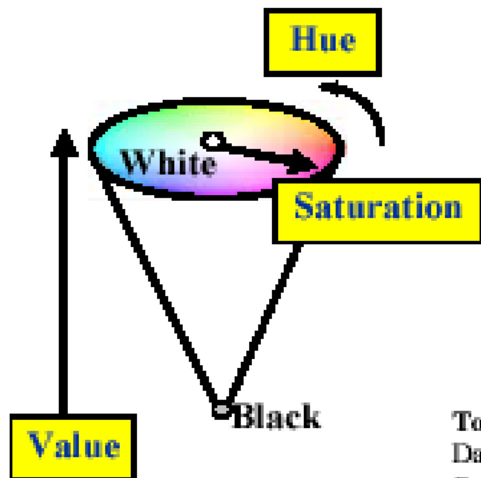
- Map (r,g,b)->(x,y,z) or (c,m,y)->(x,y,z)
- Combinations of primary color components (R, G, B) used to produce any desired color
- The two spaces are complements of each other





HSV color cone

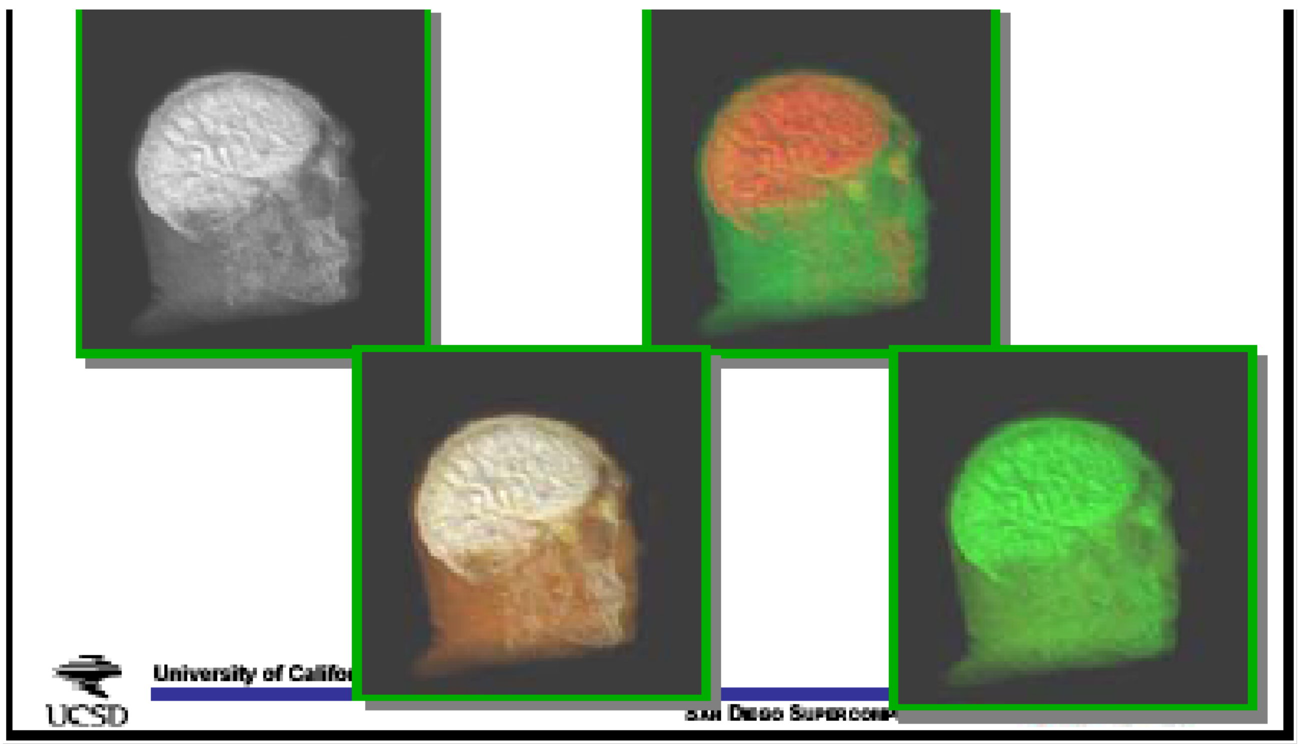
- Hue
  - the various colors we perceive
  - Each has its own unique wavelength
- Saturation
  - Also called chroma
  - Comparison of color to neutral gr
  - Richness of color
  - 100% - pure color, 0% gray
- Value
  - Lightness or darkness of a hue, or achromatic color
  - Lower when darker, higher when lighter



To convert from HSV to RGB, see: Foley, Van Dam, Feiner, and Hughes, *Computer Graphics: Principles and Practices*, Addison-Wesley, 1990.

False color representation and color maps

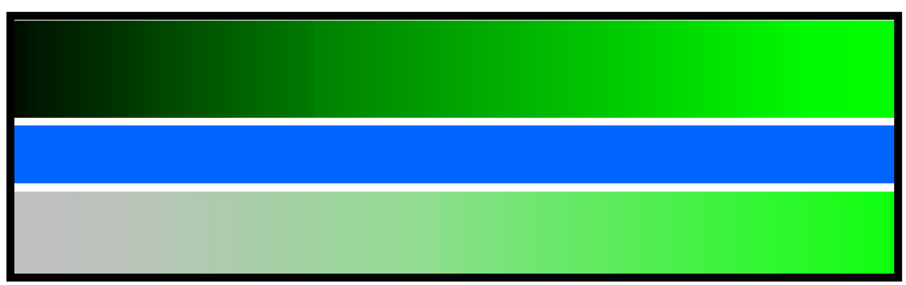
- Map values from any range to a map of colors
  - (ie a matrix of 0-1 range -> white-black)



Typical color maps

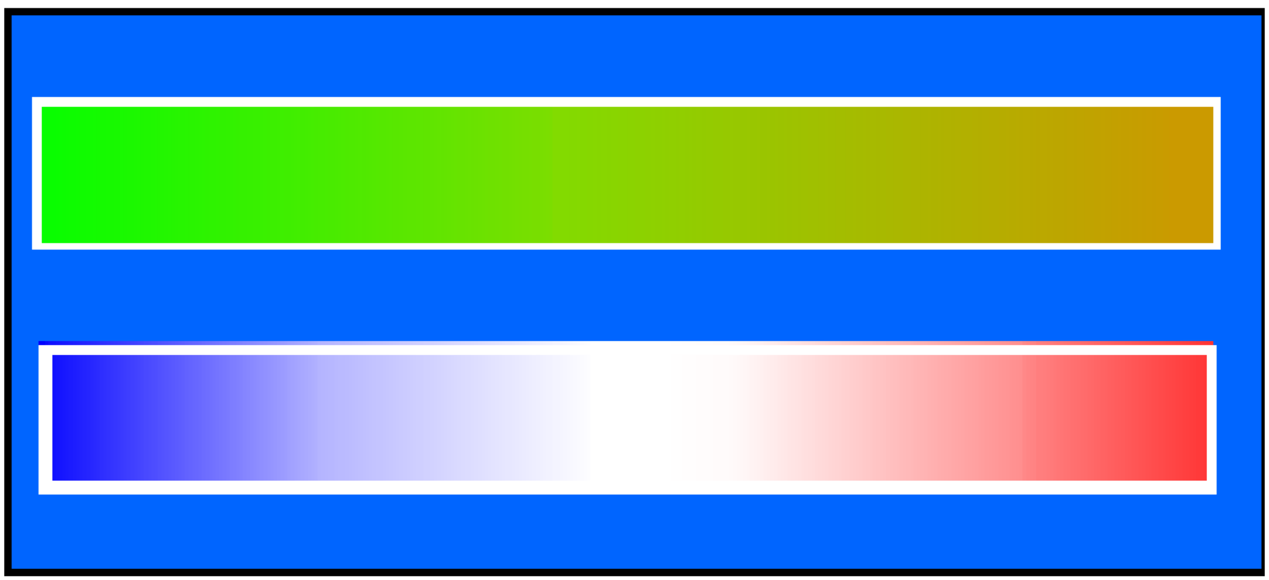
- **Gray scale** – get gray by setting all three color values to the same

- **Intensity and saturation color scales**- we often feel intuitively that black means nothing



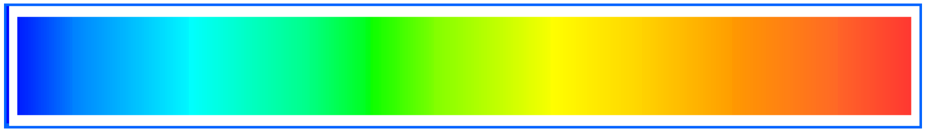
More color maps

- **Two color interpolation** – blue->red, interesting, bad visually, but strong meaning
- Generally you put white in center, otherwise magenta in middle means nothing



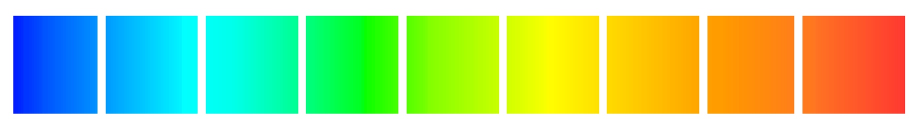
A few more color maps

- **Rainbow color scale** – magenta is not directly in the em spectrum



- **Heated object color scale** – intensity increases left -> right

- **Color scale contours**



Different display technologies have different limitations

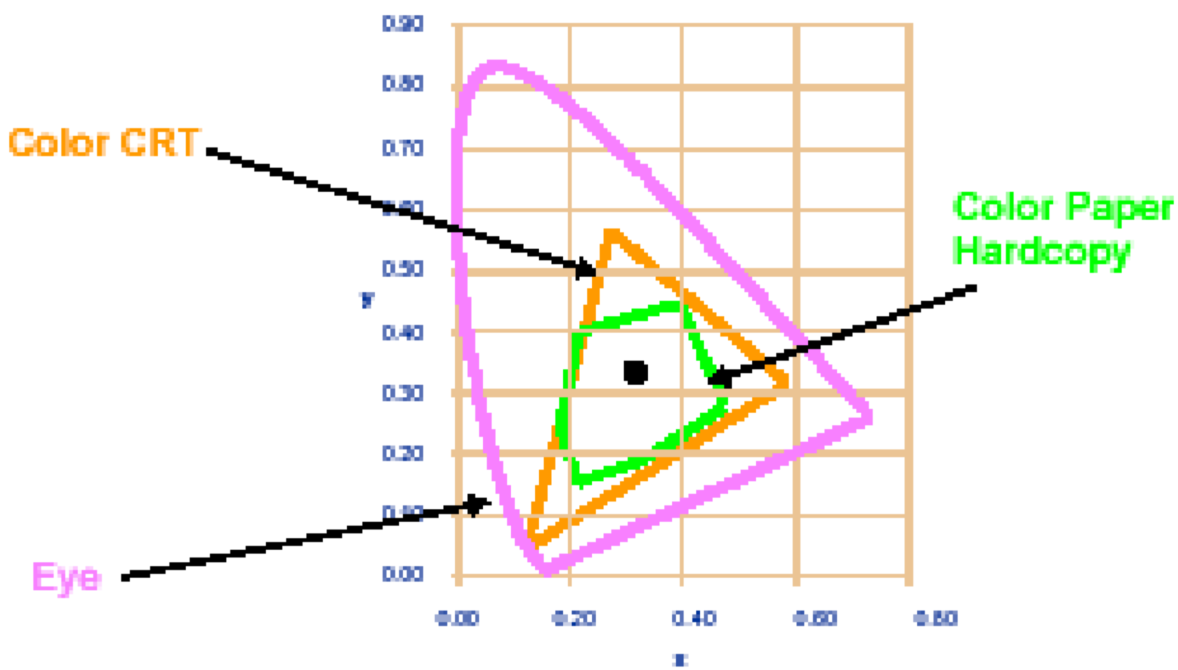
- CRT
  - Widest color gamut
  - Fast refresh for high performance VR applications
  - Still narrower gamut than human perception
  - Cheaper than LCDs
  - Multiple resolutions
- LCD
  - Slow response (‘refresh’)
  - Less colors than CRT typically, but improving
  - Tough
  - Not good for extreme temperatures
  - Multiple resolutions are interpolated, not true changes

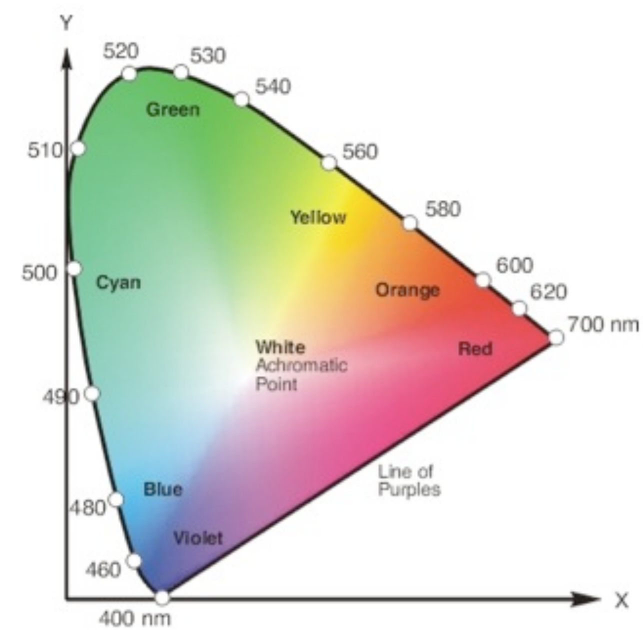
More on different displays

- Color printer
  - Subtractive color
  - Narrow color gamut
  - Realize that you may have a $500 color printer with photorealistic detail IF you use the special paper, but others may not
- NTSC TV
  - Narrow color gamut, slow refresh, interlacing
- Film
  - Fairly wide color gamut
  - Good resolution typically

Comparison of typical color gamuts

- Try to stay away from the regions which cannot be printed when creating images for papers, or convert them beforehand





Output

- If you are creating visualizations for multiple contexts (video, computer monitors, printed papers, faxes, etc) be aware of device limitations
- Use redundant encoding of information if you don’t know what the output is or who will be looking at it
  - Different fonts
  - Symbols
  - Fill pattern
  - Outline pattern
  - Outline thickness

A final word about colors…

- Just because you *have* 2^{24} different colors
- Doesn't mean you have to use them all…

Compositing

- Using color models we can blend the components together using some relationship
  - Knowing this, and how the composites work you can make things happen the way you want

Alpha blending

- Most basic - Consider three pixels;
  - fa - a foreground pixel
  - ba - background pixel
  - c - composited pixel
  - α - alpha

$$c_r = \alpha\, f_r + (1 - \alpha)\, b_r$$

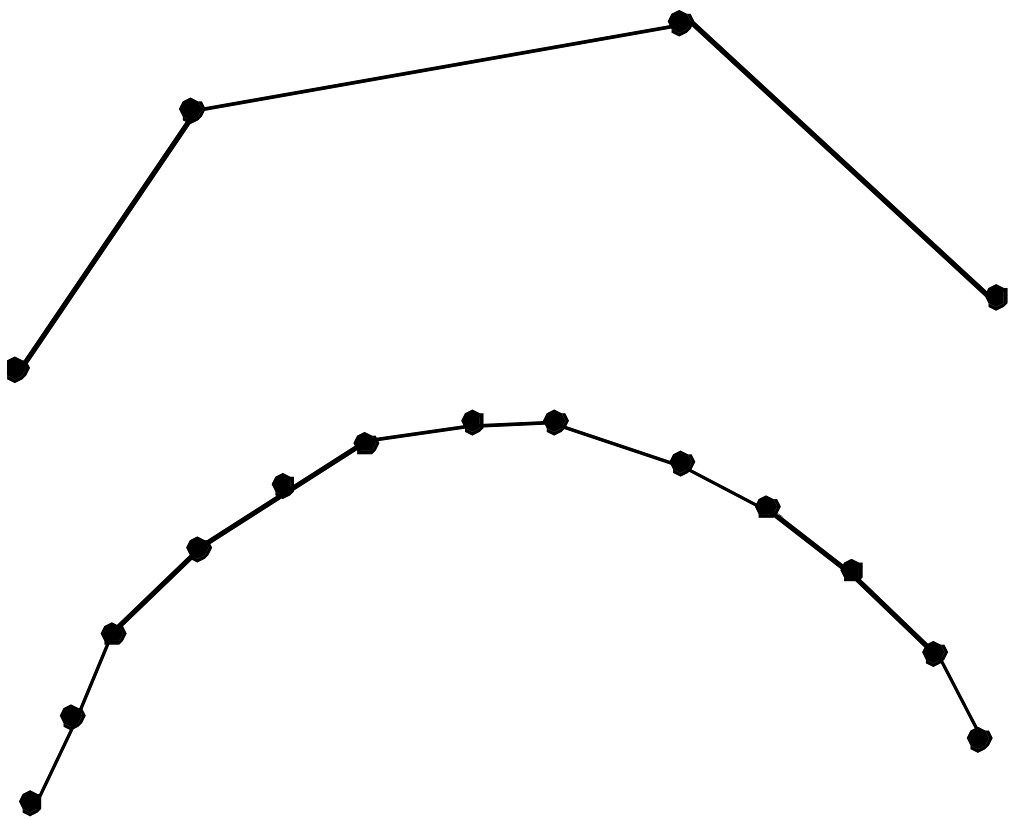
$$c_g = \alpha\, f_g + (1 - \alpha)\, b_g$$

$$c_b = \alpha\, f_b + (1 - \alpha)\, b_b$$

Curves

- Geometry
- Animation
  - Physical movement
  - Color variations/replacement
  - Blending/compositing
- Audio

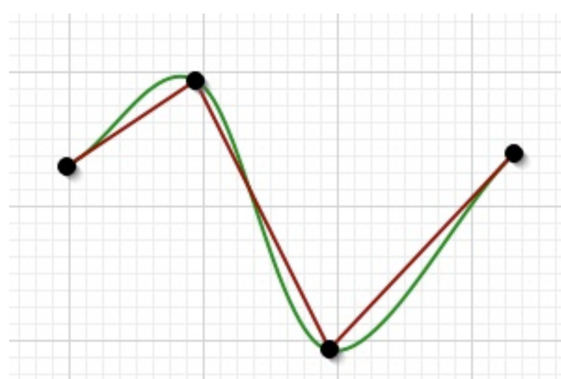
“Computers can’t draw curves.”



The more points/line segments that are used, the smoother the curve.

Interpolation

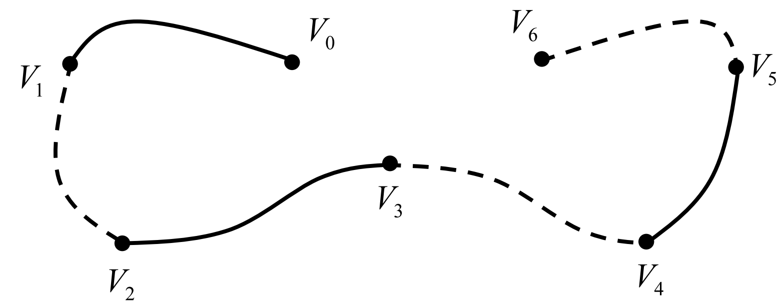
- The process of ‘reading between the lines’ of data
- Fitting a (usually smooth) curve to a limited set of data



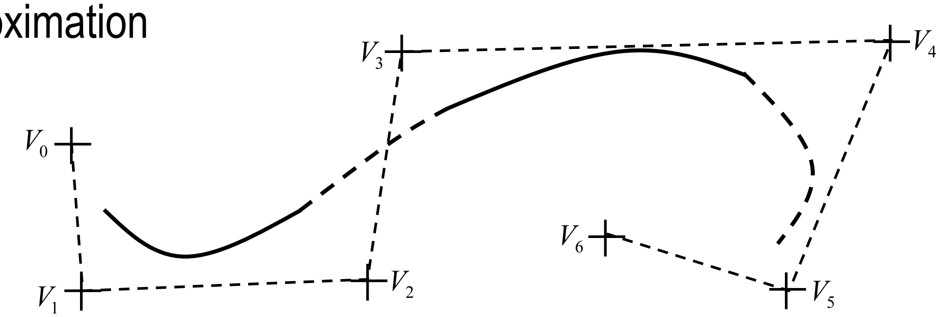
2 classes of interpolation

- Find a curve that passes through ALL the data points exactly
  - Useful for creating curves from minimal data (extrapolation)
  - Keyframing
- Find a curve that fits as closely as possible to the points
  - Useful in cases where there is uncertainty associated with the data

Interpolation

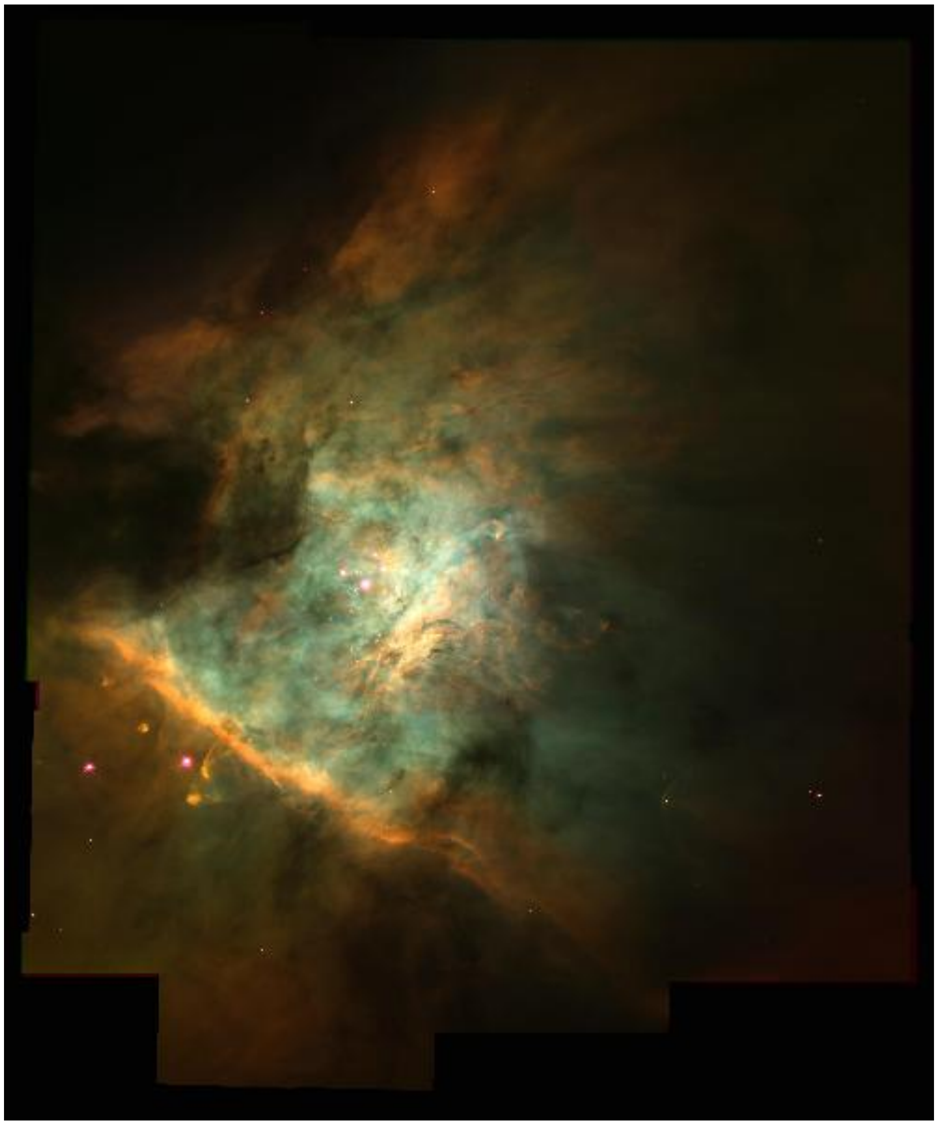


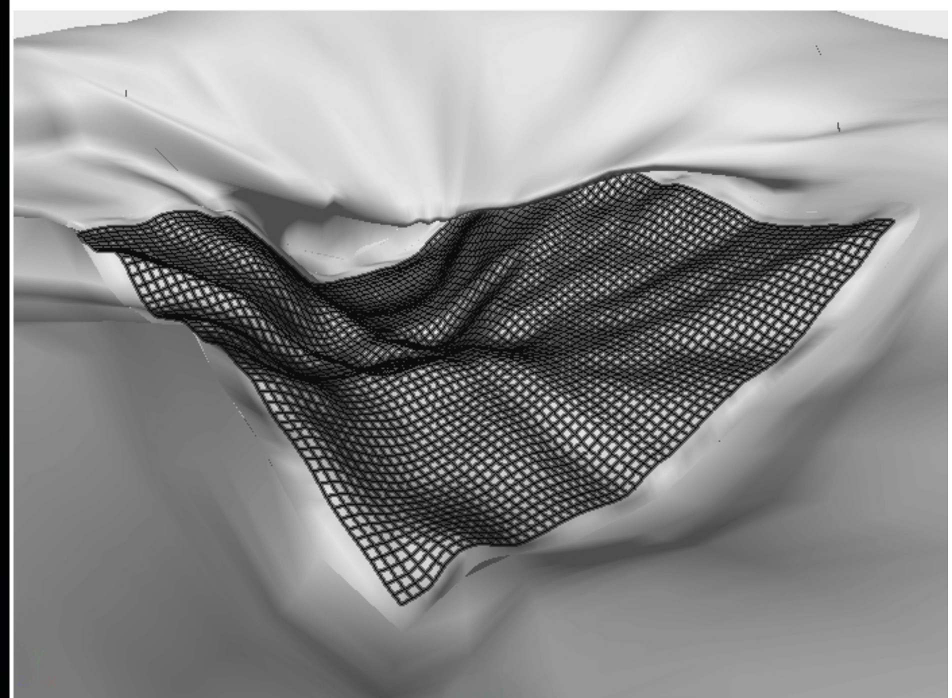
Approximation



[redacted]

Why nonlinear interpolation?





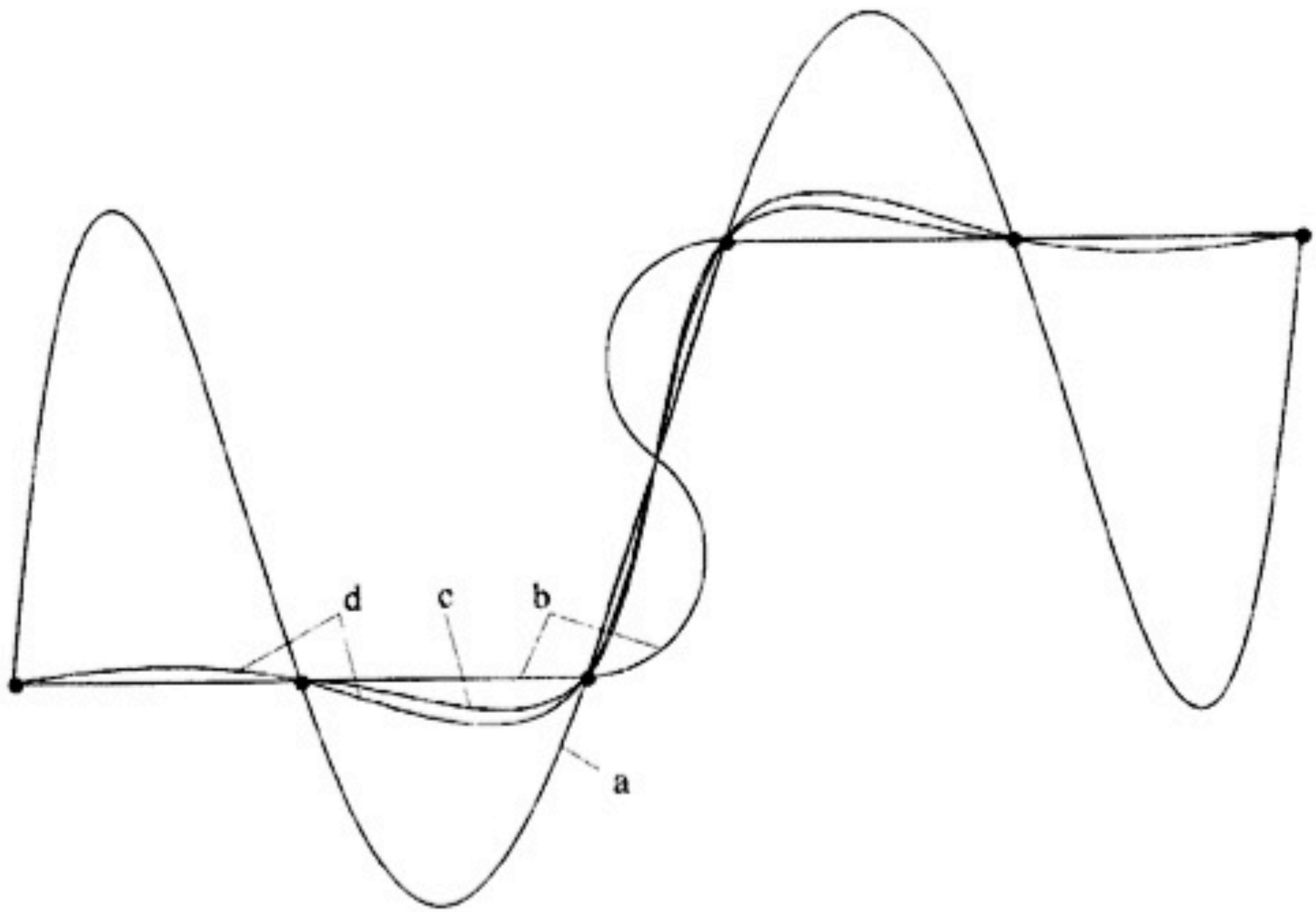
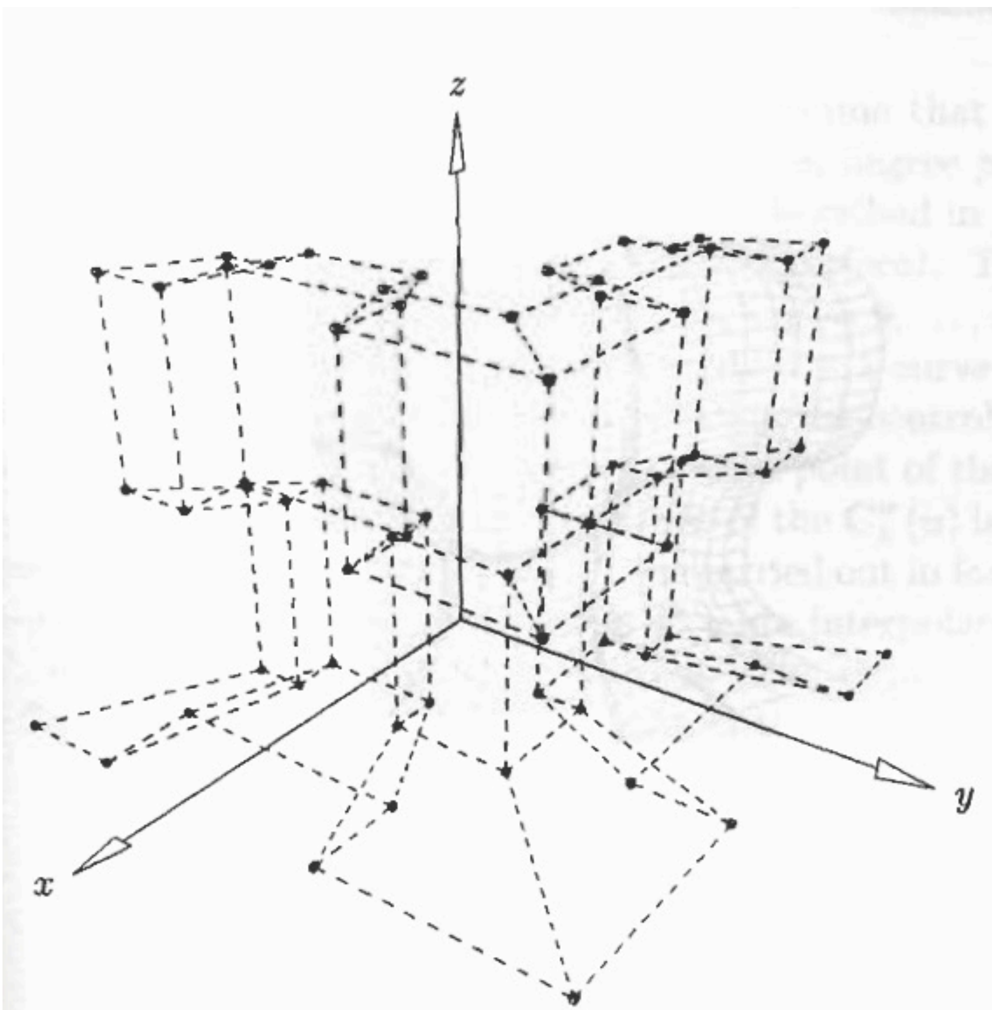
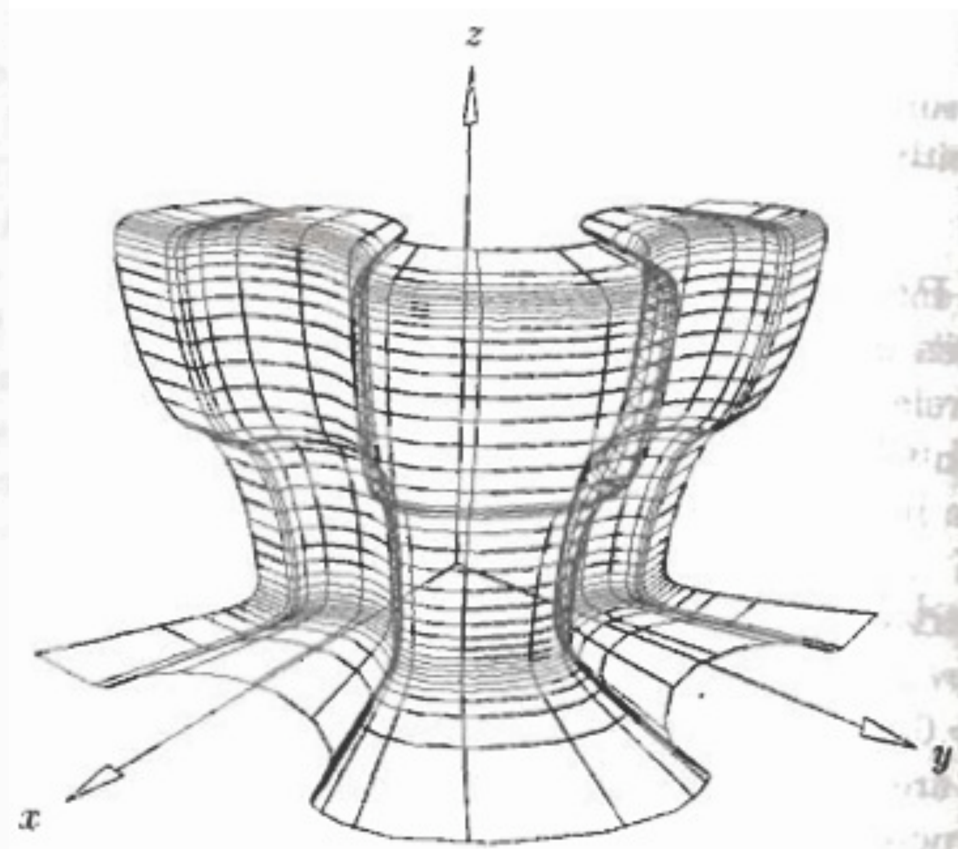


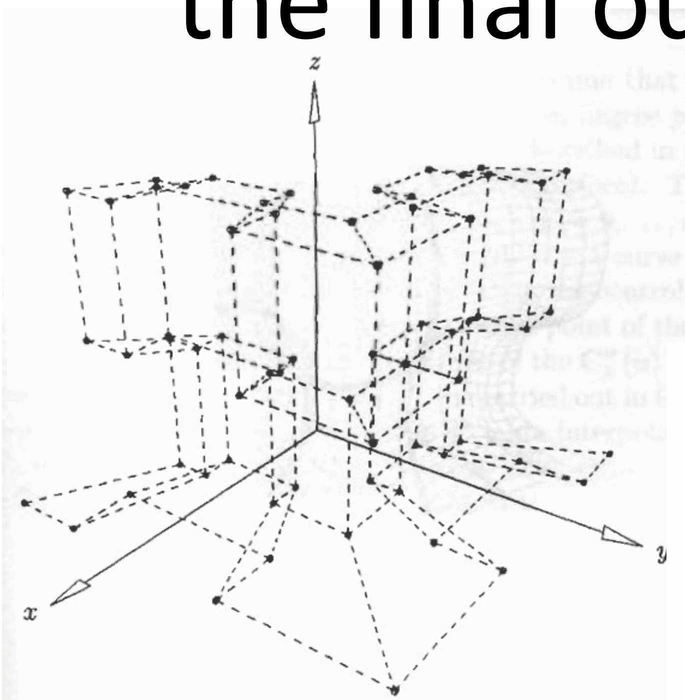
Figure 7.1 Interpolation curves drawn for six vertex points (dots), with y plotted in the vertical and x in the horizontal direction. Curves are shown for (a) a high-order polynomial fit, (b) a circular-arc fit, (c) a parabolic blend, and (d) a natural cubic spline.

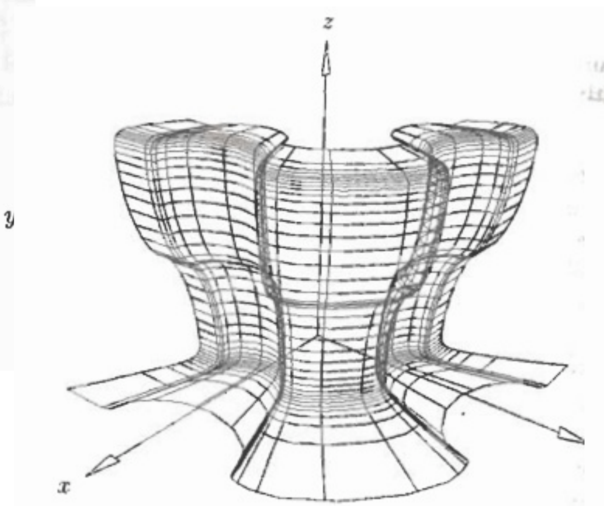
Splines are useful for N-Dimensions

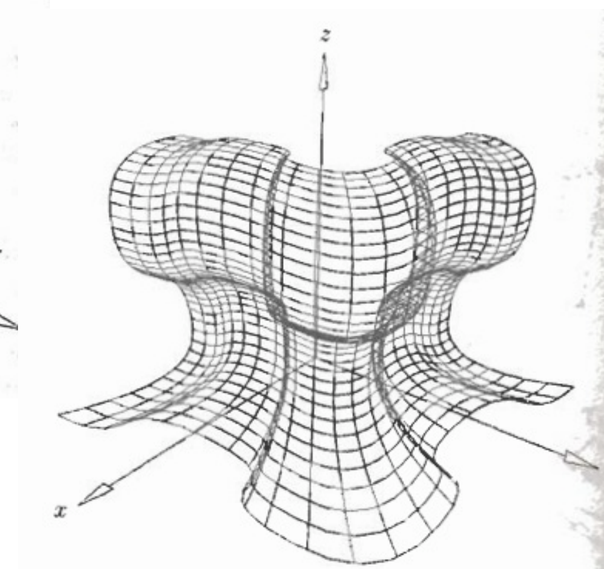




Splines also give you control over the final outcome of the curve







Some types of splines

- Natural cubic spline
- Quadratic B-Splines
- Hermite Cubic Splines
- Coons Cubic Splines
- Rational B-Splines
- NURBS (Non-Uniform Rational B-Splines)

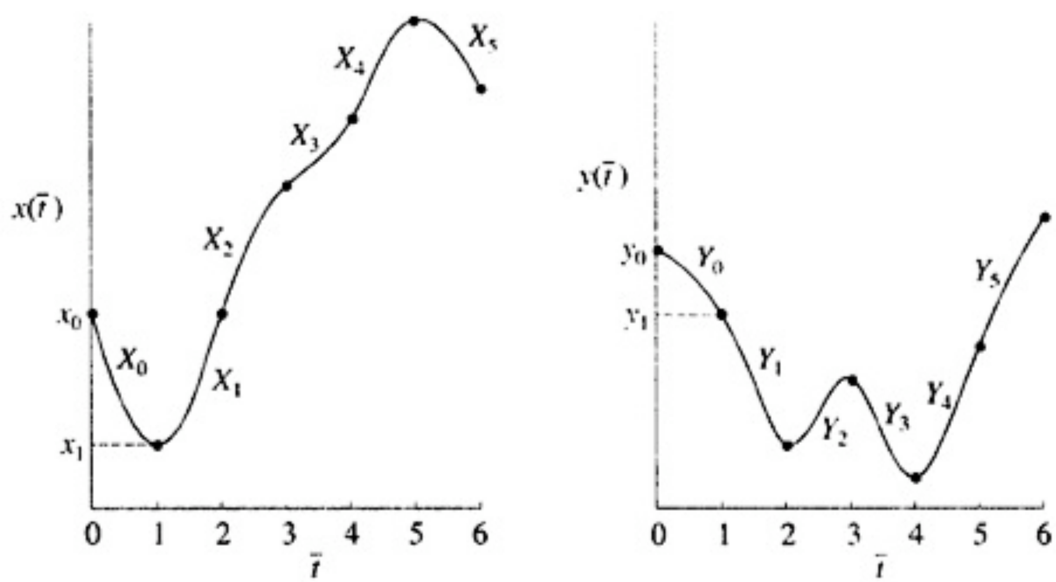
What we will discuss

- Natural cubic splines
  - Why cubic?
    - Because a curve is ‘wiggly’ and this is the lowest order polynomial that satisfies the conditions we’re going to lay out
    - Higher order gets too oscillatory

    - Elasticity equation is actually a cubic relationship between force applied and resulting curve of flexible material

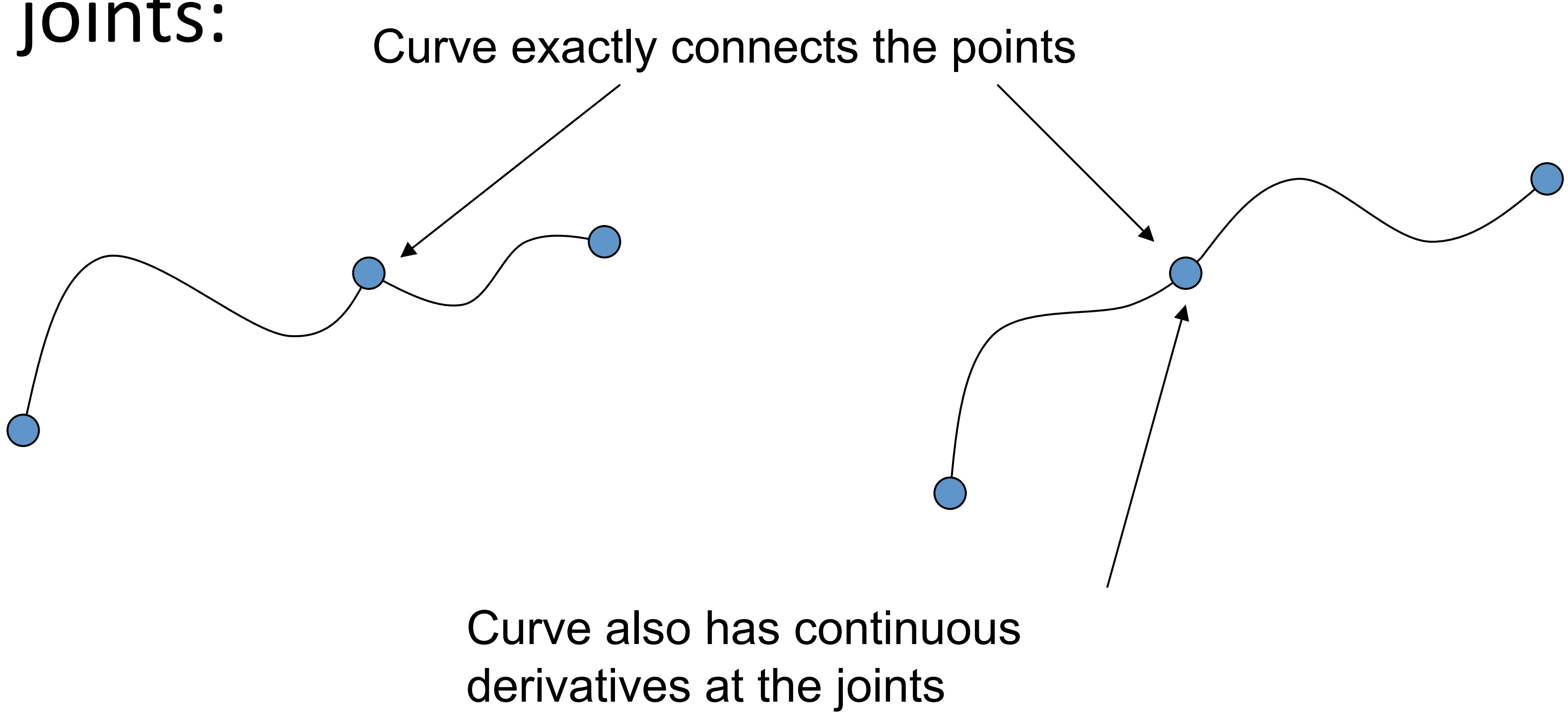
Natural Cubic Spline - a conceptual introduction

- We construct the following curves in sections



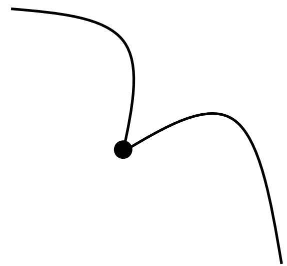
Adding constraints to solve for the unknowns

- Continuity at the joints:



Order of continuity

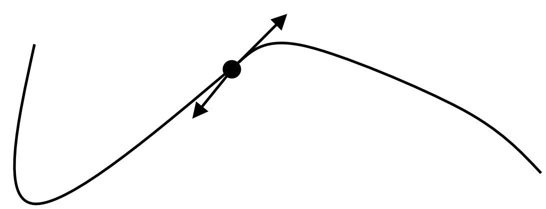
$G^{(0)}$



(a)

$C^{(0)}$ 0^{th} order continuity

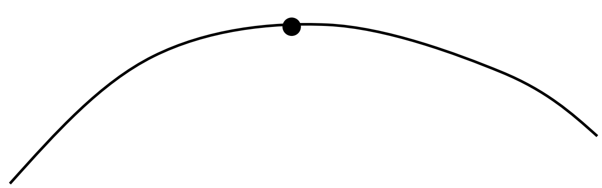
$G^{(1)}$



(b)

$C^{(1)}$ 1^{st} order continuity

$G^{(2)}$



(c)

$C^{(2)}$ 2^{nd} order continuity

Natural Cubic Splines

- We fit another parametric curve (similar to LERP), with a value of t from 0-1 again and make the ith segment according to

$$Y_i(t) = a_i + b_i t + c_i t^2 + d_i t^3$$

- And we solve for each set of these constants by requiring continuity at the end points (one section smoothly flows into the next, and the slope must match as well)

$$Y_i(0) = y_i = a_i$$

$$Y_i(1) = y_{i+1} = a_i + b_i + c_i + d_i$$

$$Y_i'(0) = D_i = b_i$$

$$Y_i'(1) = D_{i+1} = b_i + 2c_i + 3d_i$$

Vector

- "magnitude and direction"
- Collection of variables
  - 1xn or nx1
  - {position, color, scale, awesomeness}

Matrix

- More values collected together in a 2d ‘grid’
- The seats in a room
- mxn
- Previous example and values over time, perhaps

Thinking in higher dimensional spaces

- You can extend these ideas to n-dimensional spaces
  - What the heck does this have to do with art?
    - Your work is like a *hypersurface* in n-dimensions
      - Sights, sounds, colors, movement, shapes, expressions, ideas
    - The connection is like a slice in lower dimensional space through all the possibilities
      - That's why art can be seen in infinite ways
      - You can guide a person into that space of experience, take them to a place they have never been

Graphical example - evolving organisms optimize cost, maximize rewards


Thanks
• See website for more information:
• http://casimpkinsjr.radiantdolphinpress.com