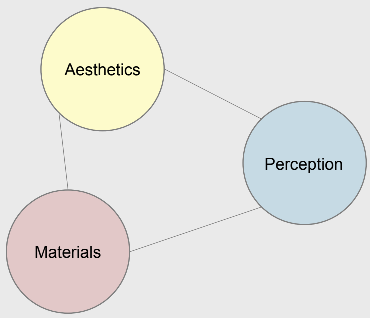
Effective Color



Value & Contrast

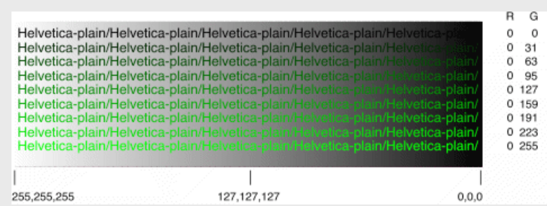
Value

Value
- Perceived lightness (Munsell value, L*)
- No edge without lightness difference
- No shading without lightness variation

Value difference = Contrast
- Defines legibility
- Controls attention
- Creates layering

"Get it right in black and white"

Controls Legibility



colorusage.arc.nasa.gov

Can you read this?

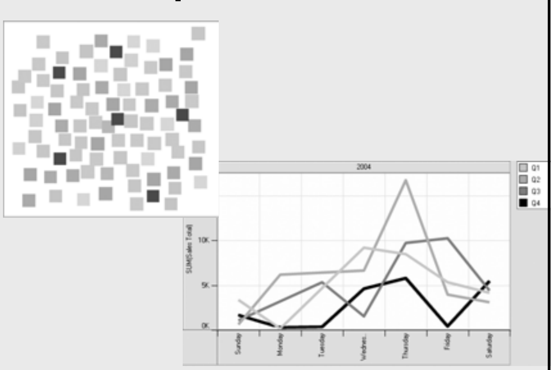
Can you read this?

Can you read this?

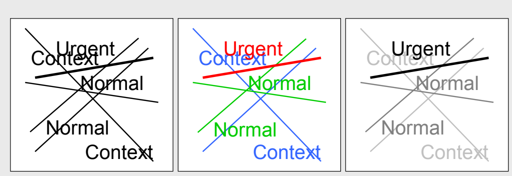
Can you read this?

Must have value contrast, NOT just hue contrast

Creates Emphasis



Creates Layers



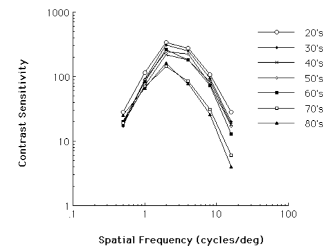
colorusage.arc.nasa.gov

Contrast

General formulation
- Luminance difference (Y_f , Y_b)
- Depends on size (spatial frequency)
- Depends on adaptation

Contrast sensitivity function
- Spatial frequency vs. luminance contrast
- Peak sensitivity around 1-3 cycles/degree
- Depends on age, acuity

Contrast Sensitivity



http://www.usd.edu/psyc301/CSFIntro.htm

Contrast Sensitivity (demo)

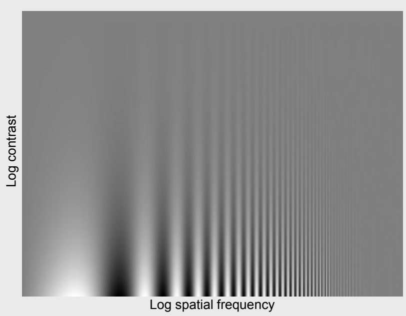


Image Courtesy of Izumi Ohzawa, Ph.D.
University of California School of Optometry

Computing Contrast

Small symbols, solid background (Weber)
- $C = (Y_f - Y_b)/Y_b$
- Adapted to background

Textures, high frequency patterns (Michelson)
- $C = (Y_f - Y_b)/(Y_f + Y_b)$
- Adapted to average

Contrast using ΔL^* (my rules of thumb)
- 1 is ideally visible
- 10 is easily visible
- 20 is legible for text

Measuring Contrast

Display luminance
- $Y = rY_R + gY_G + bY_B$
- Highly dependent on "gamma function"
- **Different for different displays**

Display contrast
- Display luminance
- Ambient light (reduces contrast)

Small objects (text, lines)
- Pixel bleed, antialiasing
- Limits of CIE (2° at 18" approx. 0.6 in)

Text legibility

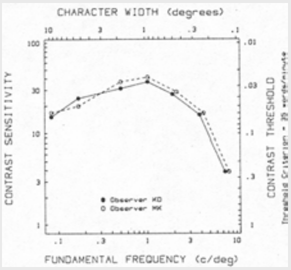
ISO Legibility
- 5:1 contrast for legibility (ISO standard)
- 3:1 minimum legibility
- 10:1 recommended for small text

Function of contrast and font size
- "Psychophysics of Reading" Legge, et. al.
- "Contrast sensitivity curve" for text

Stone's rule of thumb ($\Delta L^*=20$)

Contrast Sensitivity for Reading

Legibility as a function of contrast vs. font size



Psychophysics of Reading: V. The Role of Contrast in Normal Vision
Gordon E. Legge, Gary S. Rubin and Andrew Luebker

Readability

If you can't use color wisely,
it is best to avoid it entirely
Above all, do no harm

If you can't use color wisely,
it is best to avoid it entirely
Above all, do no harm.

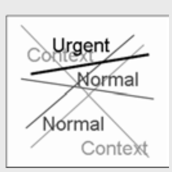
Why does the logo work?

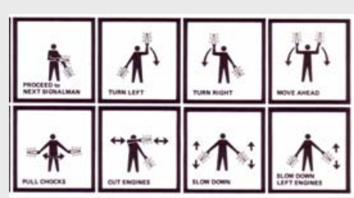
Value Control

Layering

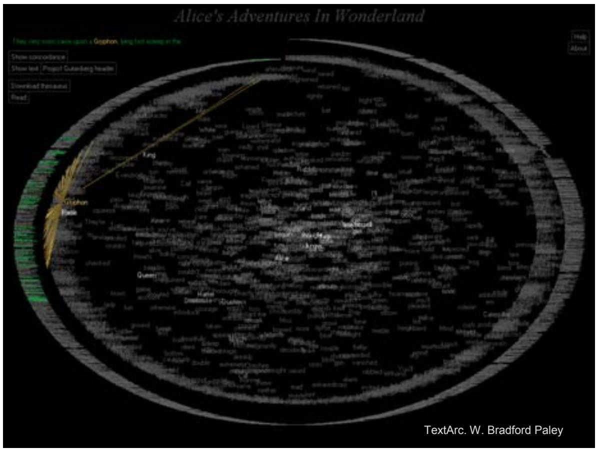
Information "layers"

- Separable, legible
- Semantic
- Variable attention

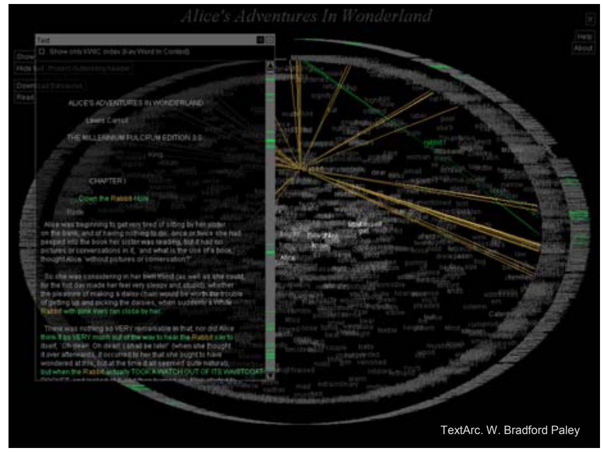




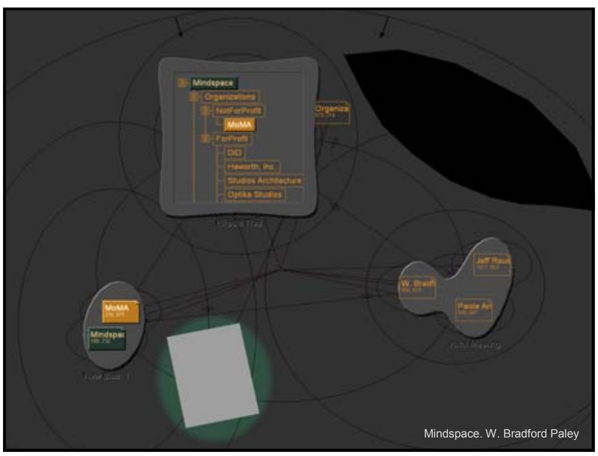
Tufte *Envisioning Information*, ch 3



TextArc. W. Bradford Paley



TextArc. W. Bradford Paley

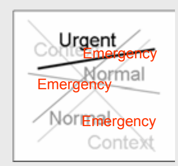


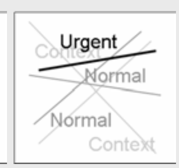
Mindspace. W. Bradford Paley

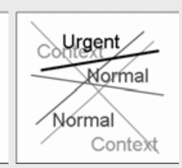
What Defines Layering?

Perceptual features
- Contrast
- Color, shape and texture

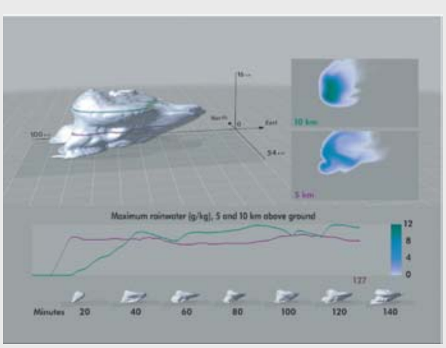
Task and attention
- Attention affects perception





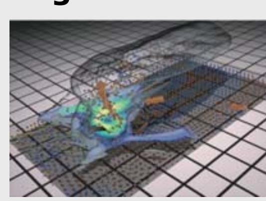
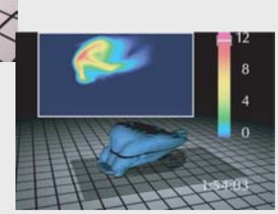


After the Storm



From "After the Storm," Baker and Bushell

Original Storm

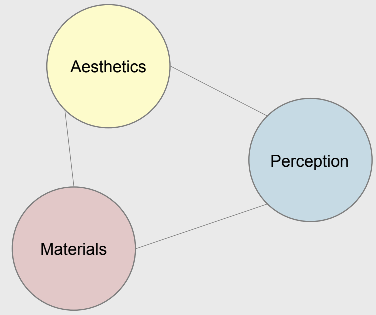
From "After the Storm," Baker and Bushell

How do Grids Work?

Grid sits unobtrusively in the background   Grid sits in foreground, obscuring map

Great Grids: How and Why? (demo at 3:00)
Maureen Stone, Lyn Bartram and Diane Gromala

Effective Color: Materials



The Craft of Digital Color

Good ideas executed with superb craft"

—E. R. Tufte

Good ideas
- Unique, specific examples
- Or, broadly applicable principles
- Subtle and complex

"Superb craft" means control

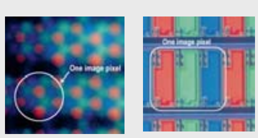
What does RGB Mean?

Values used to drive a display
Values encoded in an image
Values captured by a camera or scanner

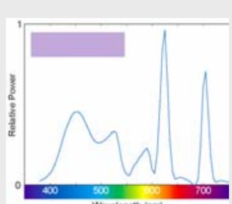
Laptop & plasma displays were the same purple color

RGB for Displays

Emissive RGB
- CRT
- LCD
- Plasma
- Projectors



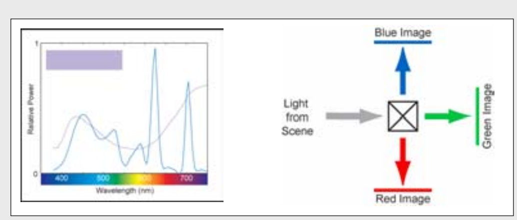
RGB values → Light



RGB from Cameras

Image capture
- Scanners, cameras
- RGB filters (not cones)

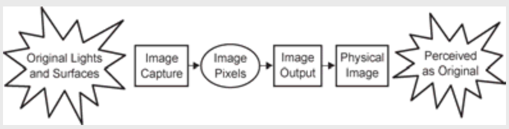
Spectra to RGB values (harder problem)



RGB in Image Encoding

Array of RGB pixels (or equivalent)
- Spatial encoding
- Color/Intensity encoding

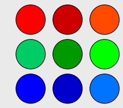
Image reproduction
- Link capture and reproduction
- Optimized process

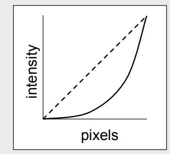


Making RGB Quantitative

Specify primary colors
- Precise hue
- Maximum brightness

Map numbers (pixels) to intensity
- Linear encodings
- Non-linear encodings
- Both are valid

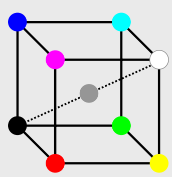




RGB Color Cube

Three primaries
- RGB lights
- Variable brightness (0..max)
- Add to create color

Characteristics
- Primaries sum to white
- Saturated colors on surface
- Gray scale along diagonal
- Cube bounds color gamut



RGB in XYZ

R,G,B are vectors

Add like vectors
- $(1,1,0) = XYZ_R + XYZ_G$

Scale like vectors
- $(s_1,0,0) = s_2 XYZ_R$
- If linear intensity encoding, $s_1 = s_2$
- If non-linear, s_2 is different than s_1

Matrix transformation
- RGB to XYZ
- Assumes linear encoding
- Inverse is XYZ to RGB

$R = (1,0,0) = XYZ_R$
$G = (0,1,0) = XYZ_G$
$B = (0,0,1) = XYZ_B$

$$M = \begin{bmatrix} X_R & Y_R & Z_R \\ X_G & Y_G & Z_G \\ X_B & Y_B & Z_B \end{bmatrix}$$

$$\begin{bmatrix} R & G & B \end{bmatrix} M = \begin{bmatrix} X & Y & Z \end{bmatrix}$$

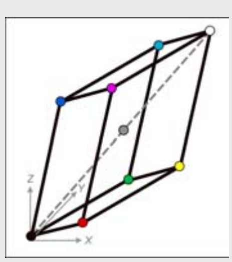
Color Cube in XYZ

Affine transformation (3x3 matrix)

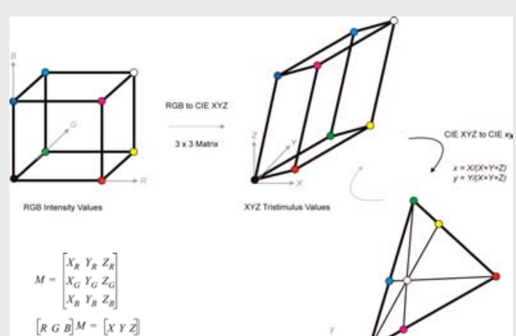
Rectangular parallelepiped

Characteristics
- Primaries sum to white
- Saturated colors on surface
- Gray scale along diagonal
- Bounds color gamut

Absolute specification



RGB to XYZ to xy



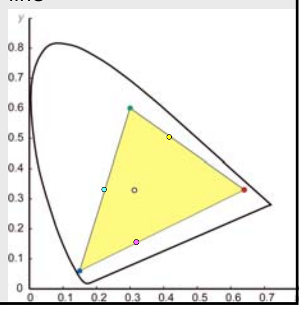
$$M = \begin{bmatrix} X_R & Y_R & Z_R \\ X_G & Y_G & Z_G \\ X_B & Y_B & Z_B \end{bmatrix}$$

$$\begin{bmatrix} R & G & B \end{bmatrix} M = \begin{bmatrix} X & Y & Z \end{bmatrix}$$

From *A Field Guide to Digital Color*, © A.K. Peters, 2003

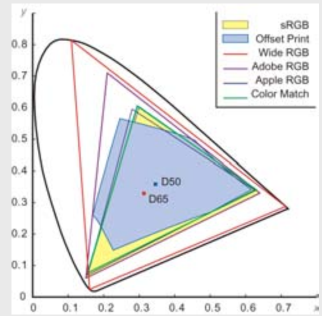
RGB Chromaticity

R,G,B are points (varying lightness)
Sum of two colors lies on line
Gamut is a triangle
- White/gray/black near center
- Saturated colors on edges



Different gamuts

Triangle = additive



Pixels to Intensity

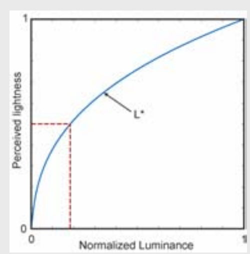
Must be carefully specified
- Measurements
- Standards

Linear
- I = kp (I = intensity, p = pixel value, k is a scalar)
- Best for computation

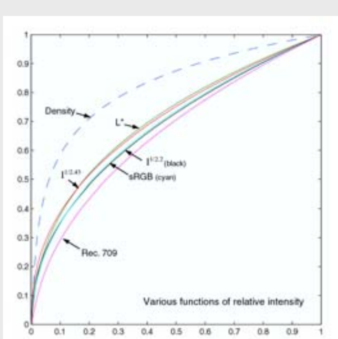
Non-linear
- $I = kp^{1/\gamma}$
- Perceptually more uniform
- More efficient to encode as pixels
- Best for encoding and display

Non-linear Encoding

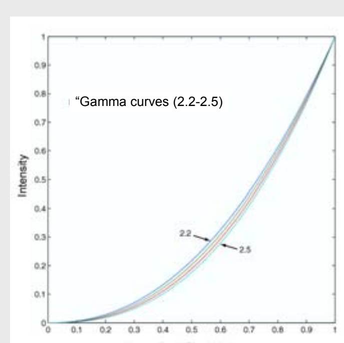
Perceptually more efficient
- Perception of brightness is non-linear wrt intensity



Many Non-linear Functions

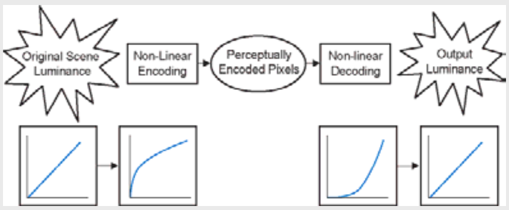


Non-linear Displays

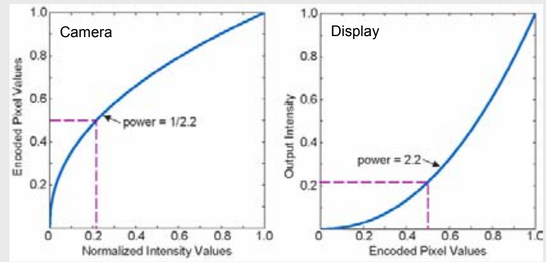


Reproducing Luminance

Encoded pixels are decoded by display



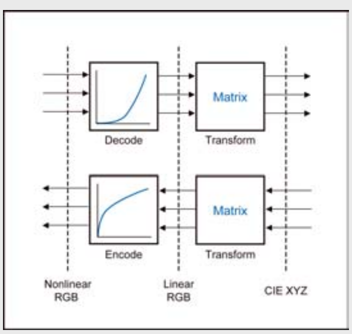
Encode/Decode



"Raw" pixels are perceptually encoded

RGB to XYZ

Pixels



XYZ

Measuring Details

Measure R, G and B independently
- Assumes scaled spectrum
- Chromaticity should be constant
- True only for CRTs

Can you just measure gray steps?
- Only if gray is a scaled spectrum
- $s_1Y_R=s_2Y_G=s_3Y_B$ for all steps (s_n constant)
- Constant chromaticity (black = white)
- "Gray balanced"

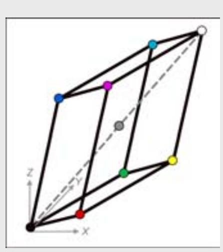
RGB to XYZ FAQ

What shape is a non-linear RGB?

Is black at XYZ = 0,0,0?

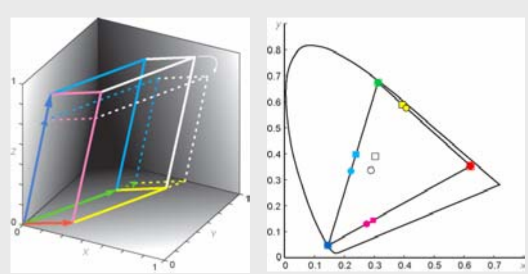
Is gray always a straight line?

What happens when
- Brightness, contrast change?
- White point changes?
- Display ages?
- Gray is not balanced?



White point changes

Change relative amounts of R, G, B



When isn't the Matrix Valid?

Assumptions
- Pixels are spatially independent
- R, G,B are independent
- Scaled pixels = scaled spectra (or scaled XYZ)
- Or, scaled pixels = same chromaticity (xy)

Common failures
- LCD displays and projectors (affects dark colors)
- DLP projectors with color wheel (RGBW)

Alternative is 3D sampling + interpolation

Tasteful Color

"Good painting, good coloring, is comparable to good cooking. Even a good cooking recipe demands tasting and repeated tasting while it is being followed. And the best tasting still depends on a cook with taste."

—Josef Albers

Successful Recipes

"You can think of an RGB or CMYK file as containing, not color, but rather a recipe for color that each device interprets according to its own capabilities. If you give 20 cooks the same recipe, you'll almost certainly get 20 slightly different dishes as a result"

Real World Color Management
B. Fraser, C. Murphy, & F. Bunting

Recipe 1

bananas
sugar
egg
butter
baking soda
baking powder
salt
flour

Bake

What is it?

Could you make it?

Recipe 2

3	bananas
1/3	sugar
1	egg
1/3	butter
1	baking soda
1	baking powder
¼	salt
1 ½	flour

Bake at 375 for 15

What is it?

Could you make it?

Banana Muffins

3	bananas
1/3 c	sugar
1	egg
1/3 c	butter
1 t	baking soda
1 t	baking powder
¼ t	salt
1 ½ c	flour

Bake at 375°F for 15 minutes

Missing process?

Could you make it?

Banana Muffins

3	bananas	Mash bananas
1/3 c	sugar	Melt butter
1	egg	Combine bananas, sugar, egg, butter
1/3 c	butter	
1 t	baking soda	Combine dry ingredients
1 t	baking powder	Add dry to wet, stir until just mixed
¼ t	salt	
1 ½ c	flour	Spoon into muffin tins

Bake at 375°F for 15 minutes

Who needs color management?

RGB to print (classic case)
Combining RGB from various sources
Creating RGB for various displays
Evaluating RGB color or its application
Transforming from RGB to scientific color models

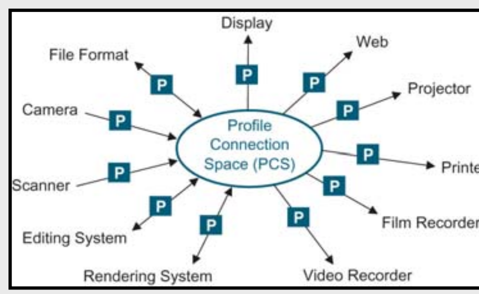
Color Management

Specify your units
- ICC profiles (CIEXYZ or CIELAB)
- Displays, printers, scanners
- File formats

Specify your process
- Color Management System (CMS)
- Manages profiles
- Performs translations

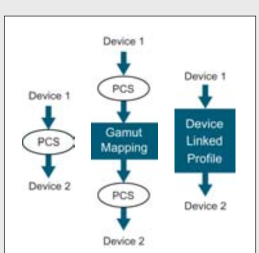
Device-Independent Color

Profiles (P) & Profile Connection Space (CIELAB)



Process

Keep all colors inside target color gamut
Maintain appearance
- Remap black/white
- Relative saturation
- Optimized for images

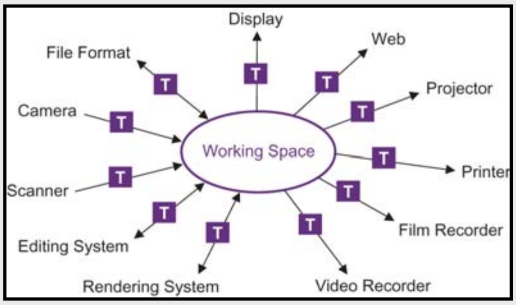


Types of profiles

Values used to drive a display (output profile)
Values encoded in an image (image profile)
Values from camera or scanner (input profile)
- Spectra to RGB; not a matrix
- Only colorimetric capture produces tristimulus values
- Otherwise, depends on spectra
- Tables, or model scanner

Scanners are easier than cameras

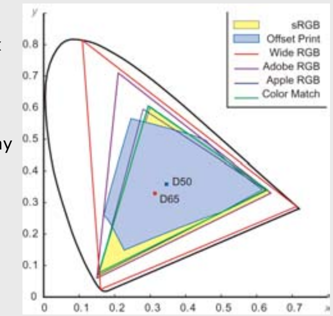
RGB Working Space



Common RGB Spaces

Gamma curve
- 2.2 for PC, Linux
- 1.8 for Mac

Linear for CG
- Rendering space
- Remap for display
- Table look-up



Monitor & Print in xyY

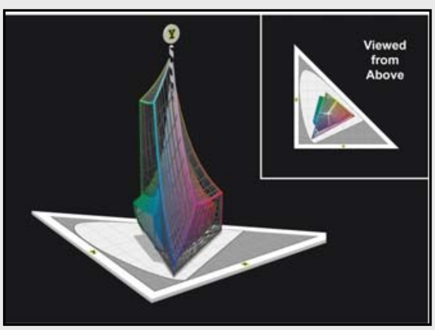


Image by Bruce Lindbloom

Considerations for RGB

Display-centered
- Easy to see all colors
- Missing some print and film colors
- Non-linear RGB (like sRGB)

Extended RGB
- Covers print, film, and display
- Must gamut map to display
- Non-linear RGB (like AdobeRGB)

Color Management Made Easy

Pick a standard RGB color space
- sRGB for web, displays, desktop printing
- Adobe RGB for film scanning
- Linear RGB for computer graphics

Characterize your display system

Control all (important) transformations

Did Tufte use Color Management?

Designed for print
- Controlled the inks (more than 4)
- Controlled the process
- Only affected by lighting

Similarly
- High quality maps
- Custom display installations
- Graphic arts before digital revolution

Color Management Examples

For the book
- Characterize my display to sRGB
- Get printer's profile
- Use Adobe tools to create CMYK

For SIGGRAPH courses
- Characterize my display to sRGB
- Create PDF tagged with sRGB
- Adjust content for projection

"Calibrated" Projector

Components
- Profile the projector
- Profile my display
- Plug-in for Powerpoint

Edit mode
- Colors are shown using display profile
- Imported images are tagged

Slideshow mode
- Copy of slides are transformed for projection
- LUTs and white point mapped to projector profile

More Examples

Digital photography
- Characterize laptop display
- Profile printer using service
- Use manufacture's scanner profile
- Use ColorSync (or Adobe tools) to manage them all

Digital photography is "killer app" for color management

Market Trends

Digital photography
- Low cost display calibration
- Printer/scanner calibration services
- "Good enough" camera and printer pairings

Home theaters
- Projector and flat panel displays
- Drive to match DVD movies and HDTV
- Trade articles, services, etc.

Characterize Your Display

Visual characterization
- Display primaries from manufacturer
- Visually set "gamma curve"
  - ColorSync or the Adobe Gamma Tool
- CRT with 2.2 gamma ~ sRGB

Buy a meter and profiling software
- Under $200 for display systems
- www.colormall.com

Hooking to the CMS

Macintosh
- Enable ColorSync
- Set display, working space, etc.

Adobe Tools
- Built into Photoshop, Illustrator, etc.
- Embedded in PSD, PDF, etc.

Hooking to the CMS

Windows ICM
- Piecewise implementation
- Drivers, .icm files
- Many improvements in Longhorn

Other applications, Linux…

Display Characterization Demo

Course Evaluations

IEEE CS will send out an email invitation
- Web-based questionaires
- About 1-2 weeks after the conference

Value
- Help define courses for the future
- Chance to win an iPod

Additional Resources

Course notes
- References
- Early copy of slides

My website
- http://www.stonesc.com/Vis06
- Final copy of slides, references

A Field Guide to Digital Color
- A.K. Peters Booth
- Discount for attending this course

Extra slides