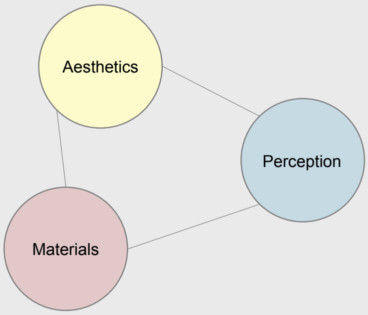
Effective Color



Value & Contrast

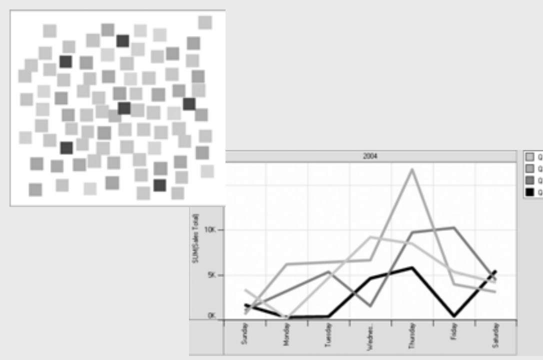
Definitions

Value
- Perceived lightness (Munsell value, L*)
- Computed from measured luminance

Contrast=value difference
- Different models based on luminance
- Depends on spatial frequency

Independent of hue

Get it right in black & white



Lightness Scales

Lightness, brightness, luminance, and L*
- Lightness is relative, brightness absolute
- Absolute intensity is light power

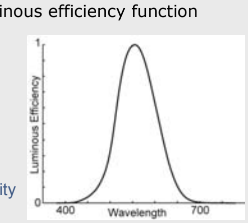
Luminance is perceived intensity
- Luminance varies with wavelength
- Variation defined by luminous efficiency function
- Equivalent to CIE Y

L* is perceptually uniform lightness

Luminance & Intensity

Intensity
- Integral of spectral distribution (power)

Luminance
- Intensity modulated by wavelength sensitivity
- Integral of spectrum × luminous efficiency function

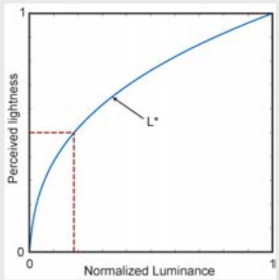


Green and blue lights of equal intensity have different luminance values

Luminance & L*

L* is a function of normalized luminance
Range 0 to100

$L^* = 116(Y/Y_n)^{1/3}-16$

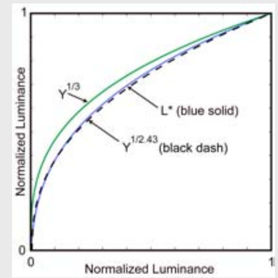


The L* Function

Combination power + linear functions
- Not 1/3 power
- Best fit is 1/2.43

$L^* \sim 100(Y/Yn)^{1/2.43}$

Similar issue in other non-linear lightness specifications



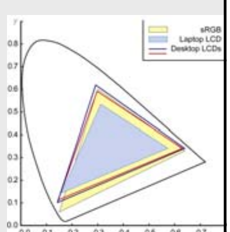
Luminance from RGB

$Y = rY_R+gY_G+bY_B$

Not a fixed equation!

Y_R,Y_G,Y_B
- Maximum luminance of RGB primaries
- Different for different displays

r,g,b
- Linear wrt luminance (intensity)
- See previous slide

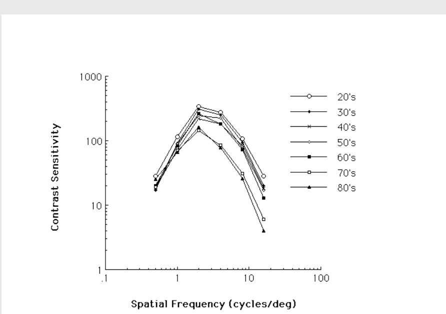


Contrast

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)

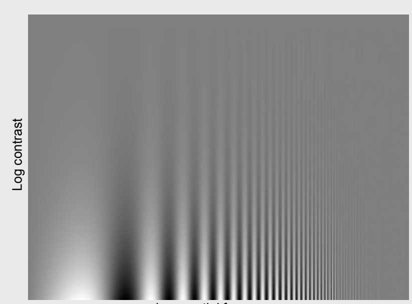


Image Courtesy of Izumi Ohzawa, Ph.D.
University of California School of Optometry

Measuring Luminance & 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)

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

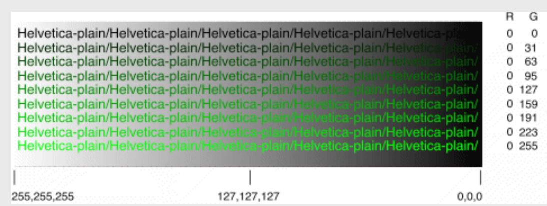
Text Legibility

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 (ΔL^*=20)

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

Why is this bad?

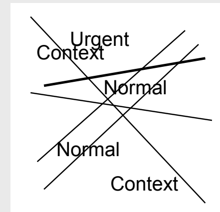
If you can't use color wisely,
it is best to avoid it entirely
Above all, do no harm

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

Why isn't this bad?

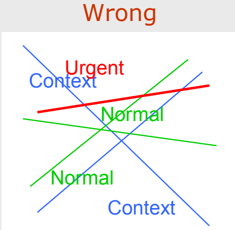
Value Control

How do we fix this?

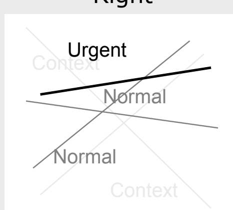


Layering

Wrong



Right

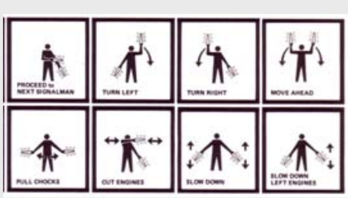


colorusage.arc.nasa.gov

Layering

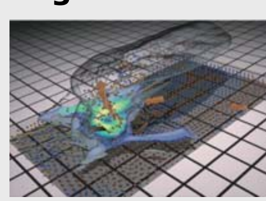
Information "layers"

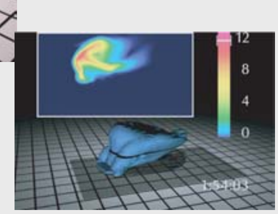
- Separable, legible
- Semantic
- Variable attention



Tufte *Envisioning Information*, ch 3

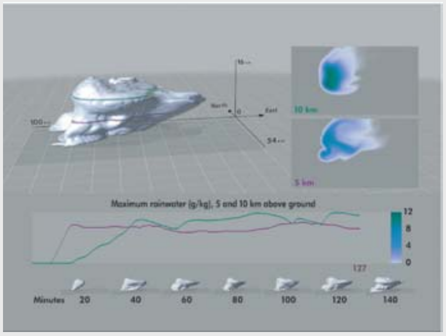
Original Storm



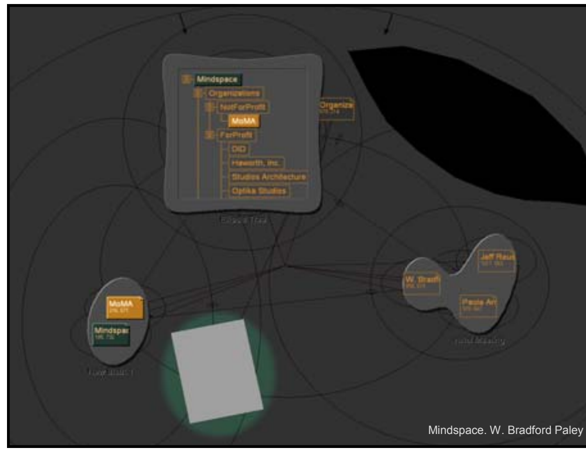


From "After the Storm," Baker and Bushell

After the Storm



From "After the Storm," Baker and Bushell



Mindspace. W. Bradford Paley

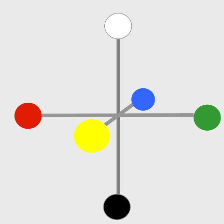
Color Vision Deficiencies (CVD)

Color Vision Deficiencies (CVD)

Non-standard cone (SML) response
- Genetic
- Medical
- Mild to missing

Three modes
- L-weak (protanope)
- M-weak (deuteranope)
- S-weak (tritanope)

Modeled in opponent space
- Achromatic axis
- R-G and Y-B axis



Incidence of Genetic CVD

Monochromacy - 0.003%

Dichromacy
- Protanopia 1%
- Deuteranopia 1.1%
- Tritanopia 0.002%

Anomalous trichromacy
- Protanomaly 1%
- Deuteranomaly 4.9%
- Tritanomaly -

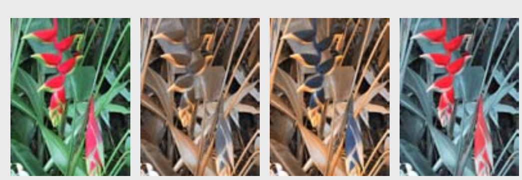
Total - 8.005%

R. W. G. Hunt. *Measuring Colour*. Fountain Press,1998.

Vischeck

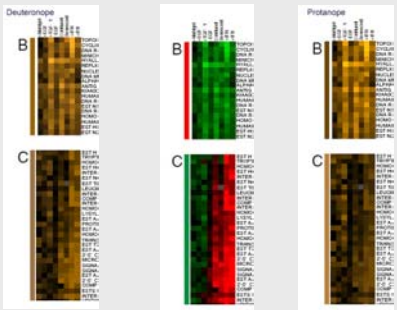
Simulates dichromatic color vision deficiencies
- Web service or Photoshop plug-in
- Robert Dougherty and Alex Wade

www.vischeck.com



Deuteranope Protanope Tritanope

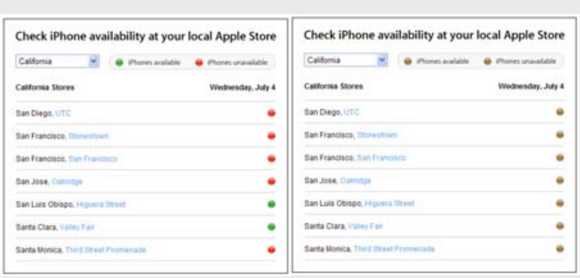
Genes in Vischeck



Red-Green Color Encoding

Rule 1: Don't do it
Rule 2: I said, don't do it
Rule 3: If you must do it provide an alternative

iPhone



Double encode: Shapes or textures

www.iloveux.com

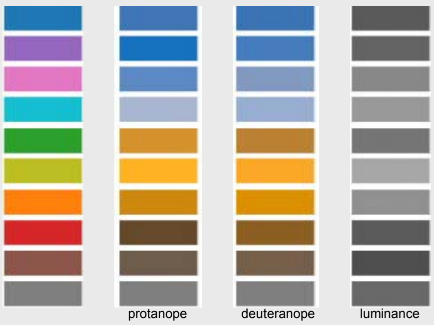
Blue is Good

Real blue (not 0,0,1) is very nice
- Add green
- Bright blue (0,0.5,1)

Sequential
- Blue-cyan
- Blue-white

Diverging
- Blue-gray-orange (blue-gray-yellow)
- Blue-gray-black

Similar colors: The real problem

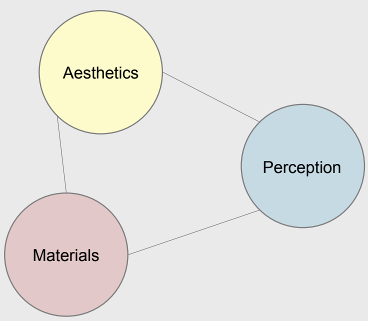


Accommodation

No color set that works for all viewers
Even accommodating most common is limiting

Options:
- Minimize dependency on color
- Double encode
- Provide choices/customization

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

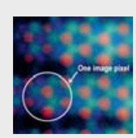
What does RGB Mean?

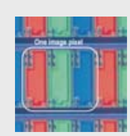
Values used to drive a display
Values encoded in an image
Values captured by a camera or scanner

Laptop & plasma displays were the same purple color

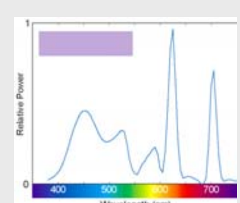
RGB for Displays

Emissive RGB
- CRT
- LCD
- Plasma
- Projectors





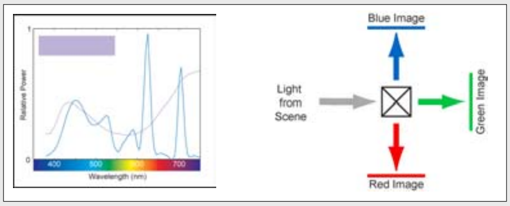
RGB values ⟶ Light



RGB from Cameras

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

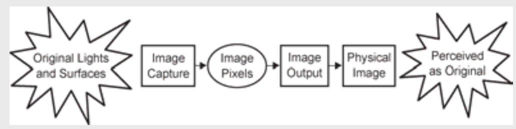
Spectra to RGB values (harder problem)



RGB in Image Encoding

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

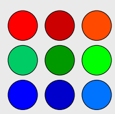
Image reproduction
- Link capture and reproduction
- Optimized process

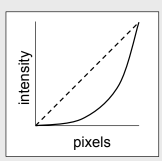


Making RGB Quantitative

Specify primary colors
- Precise hue
- Maximum brightness

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

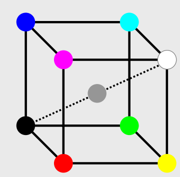




RGB Color Cube

Three primaries
- RGB lights
- Variable brightness (0 to 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

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

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

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

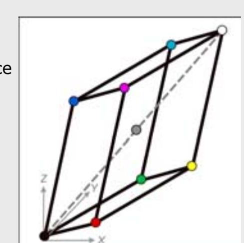
Color Cube in XYZ

Affine transformation (3x3 matrix)

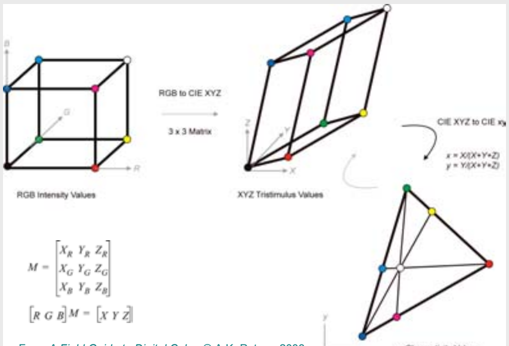
Rectangular parallelepiped

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

Absolute specification



RGB to XYZ to xy



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

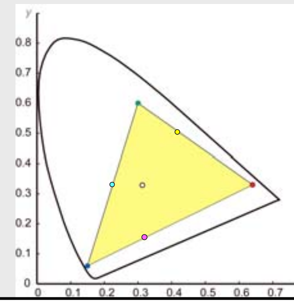
RGB Chromaticity

R,G,B are points (varying lightness)

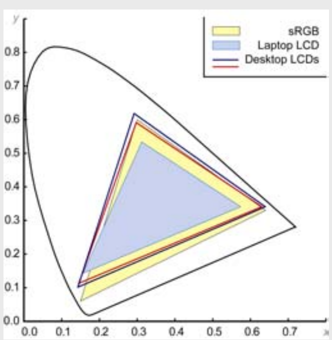
Sum of two colors lies on line

Gamut is a triangle

- White/gray/black near center
- Saturated colors on edges

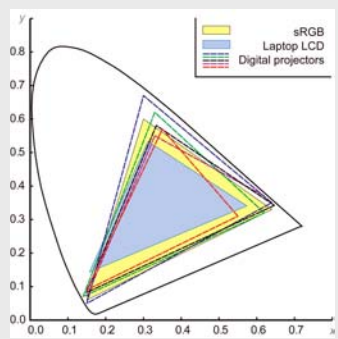


Display Gamuts



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

Projector Gamuts



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

Pixels to Intensity

Must be carefully specified

- Measurements
- Standards

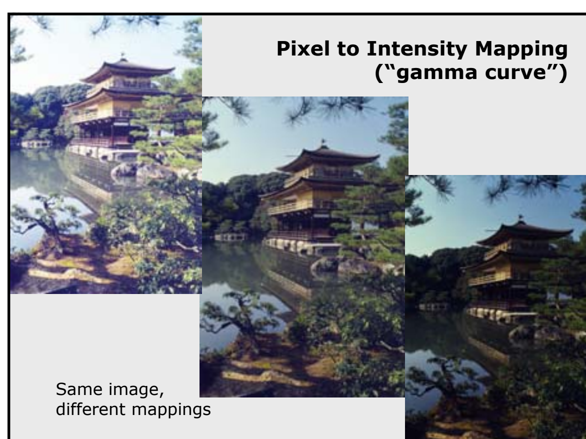
Linear

- $I = kp$ (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

Pixel to Intensity Mapping (“gamma curve”)

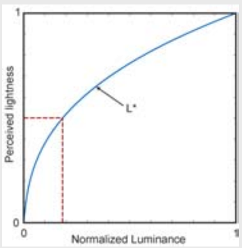


Same image, different mappings

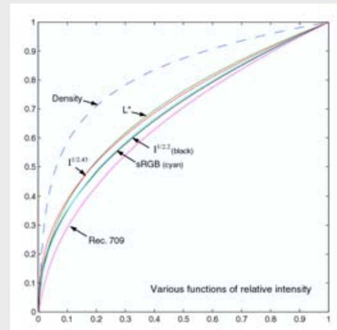
Non-linear Encoding

Perceptually more efficient

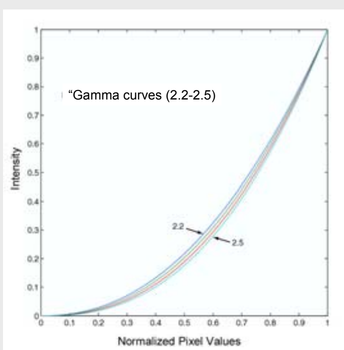
- Perception of brightness is non-linear wrt intensity



Many Non-linear Functions

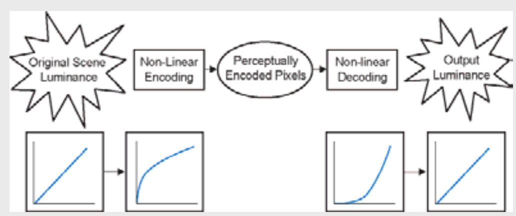


Non-linear Displays

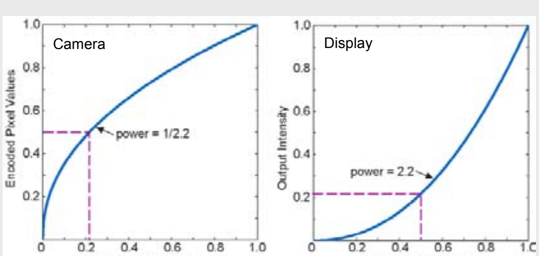


Reproducing Luminance

Encoded pixels are decoded by display



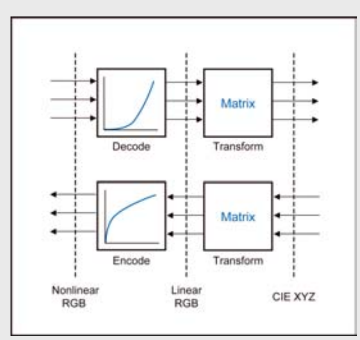
Encode/Decode



"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”

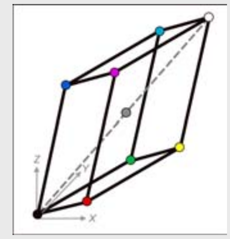
RGB to XYZ FAQ

What shape is a non-linear RGB?

Is black at XYZ = 0,0,0?

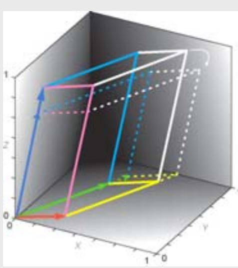
Is gray always a straight line?

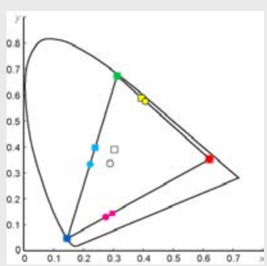
What happens when
- Brightness, contrast change?
- White point changes?
- Display ages?
- Gray is not balanced?



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
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

Mash bananas
Melt butter
Combine bananas, sugar, egg, butter
Combine dry ingredients
Add dry to wet, stir until just mixed
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

Precision required depends on the task

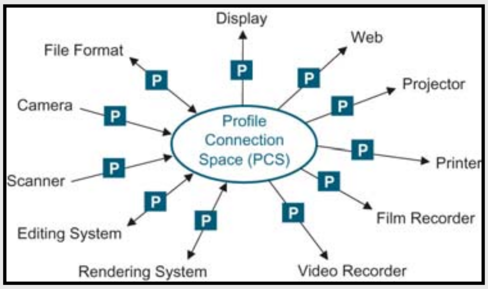
Color Management

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

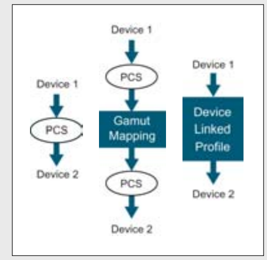
Profiles (P) & Profile Connection Space (CIELAB)



Process

Keep all colors inside target color gamut
Maintain appearance

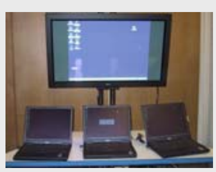
- Remap black/white
- Relative saturation
- Optimized for images



Types of profiles

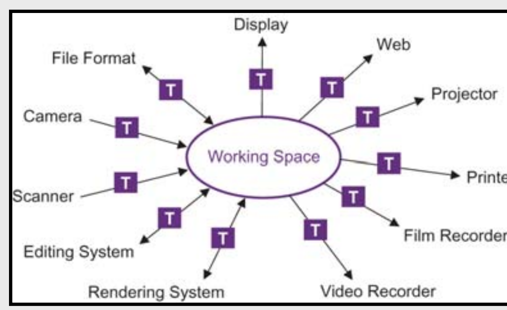
Values used to drive a display (output profile)
Values encoded in an image (image profile)
Values from camera or scanner (input profile)

- 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



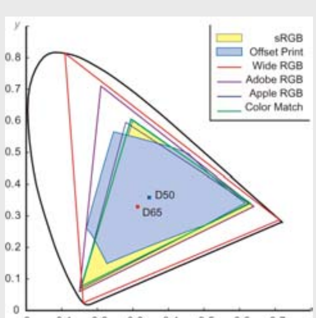
Common RGB Spaces

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

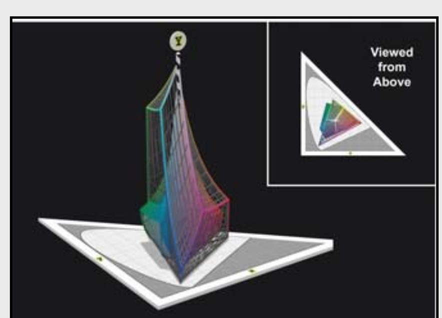


Image by Bruce Lindbloom

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

Additional Resources

Course notes
- References
- Early copy of slides

My website
- http://www.stonesc.com/Vis07
- Final copy of slides, references

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