Color in Information Display
Principles, Perception, and Models

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StoneSoup Consulting

Course 20
SIGGRAPH 2004

Description

Color is a key component of information display that is easy to use badly. As a result, Edward Tufte's key principle for color design is "do no harm." While inspired color design is an art, the principles that underlie good color design have their roots in human perception and a deep understanding of the color properties of different media. Over the last decade, there has been significant progress towards providing computational models for color perception. Similarly, there has been substantial research and engineering work that has made it easier to predict and control color in digital media. Taken together, these provide a foundation that should enable the algorithmic application of color that is robust and effective, if still not "inspired."

This course will survey the topics that support such a goal, and will provide pointers for further in-depth exploration. Topics include: Principles for the use of color in information display; principles of color design and color harmony; ways to numerically define and transform color, including visual, perceptual, aesthetic, and media-specific "color spaces;" color management systems and their application; color appearance fundamentals. The course will include an overview of some relevant research, including: automatic generation of color scales, algorithms for mapping names to colors, models for color blindness, and computational models for color appearance.

Prerequisites

This course should be accessible to all SIGGRAPH attendees able to understand basic scientific and mathematical presentation (simple graphs, diagrams and algebraic equations).

Intended Audience

This course is intended primarily for engineers and researchers involved in the development of systems and algorithms for information display, which includes visualization, illustration and the visual component of user-interface design. It may also be of interest to digital artists and designers seeking more information about the technical and perceptual factors that affect digital color design.

Schedule

0:00-0:30	Using Color in Information Display
0:30-1:00	Computational Models for Color
1:00-1:25	Color Appearance and Design
1:25-1:45	Making Color Robust

Presenter

Maureen Stone is an independent consultant working in the areas of digital color, information presentation, interaction and systems. Before founding StoneSoup Consulting, she spent 20 years at the Xerox Palo Alto Research Center where she attained the position of Principal Scientist. Her book, *A Field Guide to Digital* Color, was published by A.K. Peters in 2003. She has over 30 published papers plus 12 patents on topics including digital color, user interface technology and computer graphics. She has taught in SIGGRAPH digital color courses organized by William Cowan (SIGGRAPH '89) and Charles Poynton (SIGGRAPH '97), and presented a survey tutorial on digital color at SIGGRAPH '99-SIGGRAPH 2002. She has a BS and MS in Electrical Engineering from the University of Illinois, and a MS in Computer Science from Caltech.

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Overview and Bibliography

The goal of this course is to provide a foundation that enables the algorithmic application of color in fields such as visualization, illustration, and user-interface design. It combines the principles for using color in information display, which are based on perceptual models for color, with a deep understanding of how digital color represented as RGB triples can be accurately transformed and displayed.

Much of this course is taken from my own book, *A Field Guide to Digital Color.* This book is designed to provide an overview of the different fields that affect the application of digital color, plus pointers to in-depth references in each field.

1. Maureen Stone, *A Field Guide to Digital Color.* Natick, MA: A.K. Peters, 2003.

The course is split into four nearly equal segments. The first outlines the principles for using color in information display, including many examples. The next section provides a metric foundation for digital color, including the transformation from RGB triples to perceptual color spaces. Color appearance extends perceptual color spaces to include relative nature of color, which is influenced by all the colors in the viewing environment. The principles that underlie color design are can be directly derived from color appearance. The final section, on making color robust, is primarily about color management systems. It also covers color vision deficiencies, which affect approximately 10% of the population.

Below is a brief summary of the key points for each section, with bibliographic references.

Using Color in Information Display

The principles that define the effective use of color in information presentation have been articulated by Tufte and other experts. This section of the course is organized by Tufte's principles, the first of which is "do no harm."

Tufte's books are the canonical reference for information display, but only *Envisioning Information* has a chapter on color. There, Tufte categorizes the use of color as: to label, to measure, to represent or imitate reality, and to enliven or decorate. To this I've added using shading to represent shape, as this is such a key component of computer graphics.

Colin Ware's book is a good general reference on the perceptual principles that impact visualization.

2. Edward R. Tufte, *Envisioning Information*. Graphics Press, 1990.
3. Colin Ware. *Information Visualization: Perception for Design*, second edition. San Francisco: Morgan Kaufmann, 2004.

Color as Label

The basic abilities (and limitations) of color to label, highlight, and group is well understood. Distinctive colors "pop-out" from their background as a preattentive process. That is, it requires no cognitive thought to pick the red numbers out of a field of black ones. Pop-out has been extensively studied in perceptual psychology, and is routinely applied to information display. The work by Smallman and Boynton concludes that up to nine unique colors will "pop out" as labels, though six is a more common number. Healey's work explores algorithms for selecting color labels.

4. Harvey S. Smallman and Robert M. Boynton, "Segregation of basic colors in an information display", *J. Opt. Soc.Am. A* **7**(10), 1985-1994 (1990).
5. Healey, C. G., Booth, K. S., and Enns, J. T. "Harnessing Preattentive Processes for Multivariate Data Visualization." In Proceedings Graphics Interface '93 (Toronto, Canada, 1993), pp. 107-117.
6. Healey, C. G. "Choosing Effective Colours for Data Visualization." In Proceedings IEEE Visualization '96 (San Francisco, California, 1996), pp. 263-270.

Labeling suggest naming. Berlin and Kay first proposed a psychophysical connection between color names and color vision as part of their linguistic studies in 1969. Since then, work by Boynton and others has confirmed that color names are a fundamental part of color vision.

Berlin and Kay's anthropological work on color naming was originally published in 1969, and was reprinted in 1990. Boynton studied the psychophysical nature of color names, demonstrating that there is strong agreement across cultural boundaries on what constitutes a basic color. Lammen's thesis contains an extensive summary and bibliography. More recent work explores color naming to support image reproduction applications. Moroney's paper describes a recent experiment using the web, where people are invited to submit names for colors.

7. Brent Berlin and Paul Kay. *Basic Color Terms: Their Universality and Evolution,* University of California Press, Berkeley CA, 1991 edition, originally published in 1969.
8. Robert Boynton and Conrad Olson. "Locating basic colors in the OSA space," *Color Research and Application*, 12(2):94-105. 1987.
9. Johan M. Lammens. "A Computational Model of Color Perception and Color Naming," Ph.D. dissertation, State University of New York at Buffalo, Computer Science department. (1994). Also available on CiteSeer (http://citeseer.ist.psu.edu/)
10. Hiroyuki Shinoda, Keiji Uchikawa and Mitsuo Ikeda, "Categorized color space on CRT in the aperture and surface color mode", *Col. Res. App*. 18(5), 326-333 (1993).
11. Steve Guest and Darren Van Laar, "The structure of color naming space", *Vision Res.* 40, 723-734 (2000).
12. H. Lin, M.R. Luo, L.W. MacDonald, and A.W.S. Tarrant, "A cross-cultural colour-naming study. Part III – a colour-naming model", *Color Res. App*. 26(4) 270-277 (2001).
13. Hirohisa Yaguchi, "Color categories in various color spaces", *Proc. IS&T/SID 9th Color Imaging Conference*, 6-8, (2001). 5.
14. Robert Benavente, Francesc Tous, Ramon Baldrich and Maria Vanrell, "Statistical model of a color naming space", *Proc. CGIV 2002*: The First European Conference on Colour in Graphics, Image and Vision, 406-411 (2002).

15. Nathan Moroney, "Unconstrained web-based color naming experiment", SPIE/IS&T Electronic Imaging'03 (2003).

The work by Kelly and Judd to map color names to the Munsell color space has both scientific and commercial applications. The color-naming system designed by Berk, et. al. is a simplified model applied to the HLS pseudo-perceptual color space. Now, it is computationally plausible to implement the original mapping to Munsell. The Color Science Library is a commercial package of color transformations that includes such an implementation.

16. K.L. Kelly and D. B. Judd. *Color, Universal Language and Dictionary of Names*, National Bureau of Standards (U.S.) Special Publication 440, Washington, (1976).
17. T. Berk, L. Brownston, and A. Kaufman. "A new color-naming system for graphics languages." *IEEE Computer Graphics and Applications*. 2, 3 (1982).
18. Color Science Library, Computer Graphics Systems Development Corporation, Mountain View, CA. (www.cgsd.com)

Color Scales

The effective use of color to represent progressions of values (color scales or sequences) has been well articulated, particularly by the cartography community. Efforts to codify these principles are usually specified in terms of perceptually specified color spaces, such as Munsell and CIELAB.

In the cartographic community, Cynthia Brewer has written extensively about using color to represent data on maps, such as those produced by the census. Her work is available online at www.colorbrewer.org.

19. Bruce E. Trumbo, "Theory for Coloring Bivariate Statistical Maps," *The American Statistician*, vol. 35, no. 4, pp. 220-226, 1981.
20. Brewer, Cynthia A., **1994**, Guidelines for Use of the Perceptual Dimensions of Color for Mapping and Visualization, in *Color Hard Copy and Graphic Arts III*, edited by J. Bares, Proceedings of the International Society for Optical Engineering (SPIE), San José, Vol. 2171, pp. 54-63.
21. Brewer, C. A. 1999. Color Use Guidelines for Data Representation, *Proceedings of the Section on Statistical Graphics, American Statistical Association*, Alexandria VA. pp. 55-60.

In the field of visualization, the first reference to using perceptual color spaces for generating color scales is Robertson and O'Callaghan (1986). Since then, various authors have worked in this area. The paper by Bergman, Rogowitz and Trennish describes PRAVDAColor, which is part of a rule-based system for visualization design (IBM). Penny Rheingan's 1999 paper is a good summary of her work and other's.

22. Robertson, O'Callaghan, The generation of Color Sequences for Univariate and Bivariate Mapping, *IEEE CG&A*, 6(2):24-32. 1986.
23. Philip K. Robertson and John F. O'Callaghan, "The Application of Perceptual Color Spaces to the Display of Remotely Sensed Imagery," *IEEE Transactions on Geoscience and Remote Sensing,* vol. 26, no. 1, pp. 49-59, 1988.

24. Colin Ware," Color Sequences for Univariate Maps:" Theory, Experiments and Principles, *IEEE Computer Graphics and Applications,* Sept. 1988, pp. 41-49, 1988.
25. Larry Bergman, Bernice Rogowitz, and Lloyd Treinish, "A rule-based tool for assisting colormap selection," *IEEE:Visualization '95*, IEEE Computer Society Press, Los Alamitos, CA, pp. 118-125, 1995.
26. Penny Rheingans (1999). Task-based Color Scale Design. *Proceedings of Applied Image and Pattern Recognition* '99, SPIE, pp. 35-43.

Making Color Metric

Digital color is represented as triples of red, green and blue values. This RGB representation can be tied to perception using the principles of color measurement established by the *Commission International de l'Eclairage (CIE).* This creates a representation for color, called the CIE tristimulus values (CIE XYZ) that is the foundation for making color metric. CIE tristimulus values are often transformed to 2D chromaticity coordinates (x,y) in a way that factors out the brightness. These are plotted on a chromaticity diagram, which represents all visible colors bounded by a horseshoe shaped region.

If R, G, B values represent linear steps in the intensity of three colored lights, then there is a linear transformation between RGB and CIE XYZ. If the mapping from RGB values to intensity is non-linear, as is typical for most display systems and encodings, additional steps are needed to map to linear values.

Raw tristimulus values represent only a limited model of perception, the effect of a spectral stimulus on the retina. Perceptual models convert tristimulus values to more "intuitive" representation of color, such as hue, lightness and chroma. A key component of this conversion is the specification of lightness axis, which runs from black to white. Because the human visual system adapts to changes in lighting, there are a wide range of tristimulus values that can appear "white." All transformations from CIE XYZ to perceptual models must specify which tristimulus values are white, and similarly for black.

Early work on using perceptual models in digital color applications was hampered by their computational complexity, but this is no longer a deterrent. For example, Adobe Photoshop supports editing images represented as CIELAB values.

Wyszechki and Stiles massive *Color Science* is the standard reference for colorimetry and color psychophysics, though an introduction to these topics is included in almost any book on color and vision. Roy Bern's update of the classic Billmeyer and Saltzman *Principles of Color Technology* is a much more up-to-date reference on color, its perception, and its measurement. It includes an excellent discussion of the evolution of color difference spaces, such as CIELAB and CIE94, as well as detail about other perceptually-based color order systems

27. G. Wyszechki and W.S. Stiles. *Color Science, Second Edition.* John Wiley & Sons
28. Roy S. Berns. *Billmeyer and Saltzman's Principles of Color Technology,* third edition. John Wiley & Sons, New York, NY., 2000.

Color Appearance and Design

Color appearance, which is influenced by size, surrounding colors, and the adaptive ability of the human visual system, is complex, but progress is being made to create models that can accurately predict color appearance. Color appearance models (CAMs) begin with perceptual models and add the effect of the viewing environment, including the local illumination and the surrounding colors. There has been a major effort by the CIE on such models, including CIECAM97s, and CIECAM02.

Mark Fairchild's book is the best broad reference on color appearance models. A second edition is due soon. Josef Albers book, *Interaction of Color*, is famous for its color illustrations. The official specifications of the CIE color appearance models have been created within Division 8, whose website is www.colour.org.

29. Mark D. Fairchild. *Color Appearance Models*. Addison-Wesley (1998).
30. Josef Albers. *Interaction of Color.* Yale University Press (1963).
31. Nathan Moroney, Mark D. Fairchild, Robert W.G. Hunt, Changjun Li, M. Ronnier Luo and Todd Newman, "The CIECAM02 Color Appearance Model", IS&T/SID 10th Color Imaging Conference (2002).

Cynthia Brewer has written specifically on the problem of simultaneous contrast in information display.

32. Brewer, Cynthia A., 1992, Review of Colour Terms and Simultaneous Contrast Research for Cartography, *Cartographica* 29(3&4): 20-30.
33. Brewer, Cynthia A., 1996, Prediction of Simultaneous Contrast between Map Colors with Hunt's Model of Color Appearance, *Color Research and Application* 21(3): 221-235.

Color Design and Selection

Wong's books on design are systematic and elegant in a way that should appeal to many in the computer graphics field. His *Principles of Color Design* is based on the Munsell (www.munsell.com) color ordering system. The primary focus of Anne Spalter's *The Computer in the Visual Arts* is to explain digital technology to the artist, but also serves well to enlighten the technologist about art and design. Anne's book also includes a good description of the classic computer graphics color selection spaces, HSV and HLS, whose original references are also included below.

34. Wucius Wong. *Principles of Color Design, second edition.* John Wiley & Sons, NY, 1997.
35. Anne Morgan Spalter, *The Computer in the Visual Arts*. Addison-Wesley, Reading, MA, 1999.
36. Alvy Ray Smith "Color gamut transform pairs," *Computer Graphics*, 12(3):12-25. (1978).
37. "Status Report of the Graphics Standards Planning Committee," *Computer Graphics* 13(3), August (1979).

The TekHVC space and the TekColor Picker were developed by Tektronics in the late

1980's, as was the work at Xerox on MetaPalette. Both used a perceptual space for color selection. TekHVC directly addressed the problem of designing across color gamuts. MetaPalette included geometric interpretations of color harmony. The MetaPalette evolved into the Canon Color Advisor. Meier, et. al's work is much more recent and extensive application of perceptual color principles to color selection.

38. J. M. Taylor, G. M. Murch and P. A. MacManus. "Tektronix HVC: A Uniform Perceptual Color System for Display Users," *SID 88 Digest*, pp.77-80, May (1988).
39. G. Beretta. "Color Palette Selection Tools," SPSE's 43rd Annual Conference, The Society for Imaging Science and Technology, 20-25 May 1990, Rochester (New York, USA) pp. 94-96 (1990).
40. L. Lavendel and T. Kohler. "The Story of a Color Advisor," Sixth IS&T/SID Color Imaging Conference (Scottsdale, AZ, November 1998), pp: 228-232. (1998).
41. Barbara J. Meier, Anne Morgan Spalter, David Karelitz, Interactive Palette Tools, to appear in IEEE Computer Graphics and Applications, 2004.

Making Color Robust

Representing digital color as perceptual values is the foundation for digital color management systems (CMS). In a color management system, *profiles* provide a metric for converting between device-specific color representations, such as the inputs to a digital display or printer, and device-independent representations, such as CIE XYZ and CIELAB. Images are reproduced by mapping them through this representation, which is called the *profile connection space*. Once used only by high-end graphic arts production houses, color management systems and their supporting color measurement technologies are becoming ubiquitous and affordable.

Robert Hunt's *The Reproduction of Colour* is an invaluable reference for color reproduction technology. It's 6th edition is due out this year. Phil Green's *Understanding Digital Color* is an excellent reference for the all-digital world of the modern graphic arts, including digital scanning, printing and color management. It is also very nicely illustrated. Giorgianni and Madden's *Digital Color Management* is a well-written book with a strong engineering orientation. It is beautifully produced, printed in full color, with some of the nicest illustrations around. Charles Poynton, who regularly teaches about digital color at SIGGRAPH, includes a description of image color specification and management in his books on video and television.

42. R.W.G. Hunt. *The Reproduction of Colour, Fifth Edition.* Fountain Press, England (1996).
43. Phil Green, *Understanding Digital Color.* 2nd edition, GATFPress, Pittsburgh (June 1999).
44. E.J. Giorgianni and T. E. Madden. *Digital Color Management.* Addison-Wesley (1998).
45. C. A. Poynton. *A Technical Introduction to Digital Video*. John Wiley & Sons (1996).
46. Charles. A. Poynton. *Digital Video and HDTV Algorithms and Interfaces.* San Francisco: Morgan Kaufmann, (2002).

47. L.W. MacDonald and A.C. Lowe, *Display Systems,* John Wiley and Sons (1997).
48. E.H. Stupp and M. S. Brennesholtz, *Projection Displays,* John Wiley and Sons (1999).

Modeling color vision deficiencies

Approximately 10% of the population, mostly male, has abnormal color vision. This does not mean that they do not see colors, but that they do not see the same 3-dimensional space of colors that "normal" people do. Most of these color vision deficiencies can be classified as errors in the red-green processing of color, with a small percentage along the blue-yellow dimension. The most common forms of "colorblindness" have been modeled in a way that their effects can be simulated. The website www.vischeck.com provides both a web service and a Photoshop plug in that can be used to check the appearance of images and designs.

49. H. Brettel, F. Viénot, and J. D. Mollon (1997) Computerized Simulation of Color Appearance for Dichromats. J. Opt. Soc. Am. A 14, 2647 - 2655.
50. Robert Dougherty and Alex Wade, Vischeck, www.vischeck.com

Slides

The slides presented in these notes are approximately the version that will be presented in the course. A final version will be made available on my website at the time of the conference.

In the printed version of these notes, color plates will appear at the end of the slides that contain selected images and illustrations that only work when seen in color.

SIGGRAPH2004

Color in Information Display

Principles, Perception and Models

Maureen Stone, StoneSoup Consulting

Information Display

SIGGRAPH2004

- Visualization
- Illustration
- Cartography
- User-interface design
- Multi-scale imaging
- Medical imaging
- …

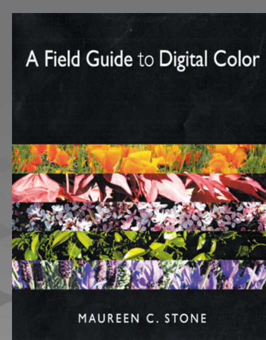
Goals for this Course

SIGGRAPH2004

- Introduce design principles (Tufte)
- Relate principles to:
  - Vision and perception
  - Design and aesthetics
  - Digital color models
- Computational tools and models
- Focus on RGB (additive) color
- Relevant research in various fields

A Brief Plug

SIGGRAPH2004



"Inspiration" for this SIGGRAPH course

Outline

SIGGRAPH2004

- Tufte's principles, examples
- Making color quantitative
- Color design & appearance
- Making color robust

Tufte's Principles

SIGGRAPH2004

- Above all, do no harm —*E. R. Tufte*
- Fundamental uses
  - To label
  - To measure
  - To represent or imitate reality
  - To enliven or decorate

Envisioning Information
Edward R. Tufte

Do No Harm

careful color

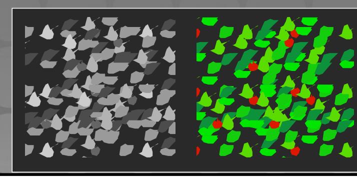
careful color

careful color

careful color

To Label

- Color as a noun
  - Identify (uniqueness and distinctness)
  - Highlighting and emphasis
  - Grouping and segmentation
  - Layering (foreground and background)



Information Visualization
Colin Ware

Count the 7's

13579345978274055
24937916478254137
23876597277103876
19874367259047362
95637283649105676
32543787954836754
56840378465485690

Time proportional to the number of digits

13579345978274055
24937916478254137
23876597277103876
19874367259047362
95637283649105676
32543787954836754
56840378465485690

Time proportional to the number of 7's

13579345978274055
24937916478254137
23876597277103876
19874367259047362
95637283649105676
32543787954836754
56840378465485690

Both 3's and 7's "Pop out"

- Typically, 5-6 distinct values simultaneously
- Up to 9 under controlled conditions

Grouping, Highlighting

	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
red	25.37	13.70	0.05	26.27	14.13	0.04	18.41	10.16	0.05	17.43	9.30	0.00
green	22.14	51.24	0.35	20.68	49.17	0.44	21.11	46.00	0.20	16.36	37.95	0.12
blue	13.17	3.71	74.89	15.38	5.20	86.83	11.55	3.37	65.53	9.96	3.44	56.14
gray	63.46	73.30	78.05	64.66	71.99	90.08	52.96	62.49	67.99	45.54	53.65	58.14
black	0.66	0.70	0.77	0.63	0.66	1.09	0.47	0.58	0.70	0.44	0.54	0.71

Group rows

	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
red	25.37	13.70	0.05	26.27	14.13	0.04	18.41	10.16	0.05	17.43	9.30	0.00
green	22.14	51.24	0.35	20.68	49.17	0.44	21.11	46.00	0.20	16.36	37.95	0.12
blue	13.17	3.71	74.89	15.38	5.20	86.83	11.55	3.37	65.53	9.96	3.44	56.14
gray	63.46	73.30	78.05	64.66	71.99	90.08	52.96	62.49	67.99	45.54	53.65	58.14
black	0.66	0.70	0.77	0.63	0.66	1.09	0.47	0.58	0.70	0.44	0.54	0.71

Group columns

Perceptual Principles

- "Pop out"
  - Preattentive perceptual process
  - Others: Angle, motion, texture, shape
- Color names
  - Cognitive process
  - Fundamental
  - Cross-cultural

To Measure

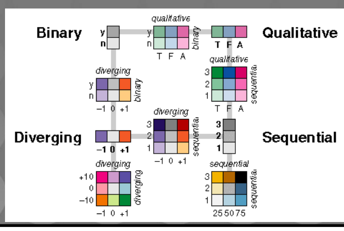
- Color as quantity
  - Few intuitive orderings
  - Grayscale, saturation scales
  - Creates clusters of similar values
- Examples
  - Thermometer scales
  - Density plots
  - Thematic maps

"Tilebars" —Marti Hearst

Color Scales

SIGGRAPH2004

- Path through color space
- Intensity, density, or saturation
- NOT hue alone if sequence matters



"Color Brewer"
Cynthia Brewer

Perceptual Principles

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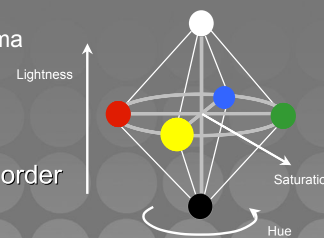
- Perceptual ordering of color
  - Lightness, value
  - Saturation, chroma
  - Hue circle

No "intuitive" hue order



Avoid "The Rainbow"

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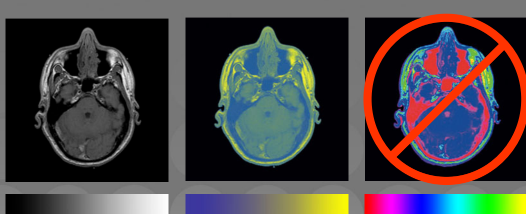

Density = Lightness

Density = Lightness
Plus change hue

Density = Hue
WRONG!

To Represent or Imitate Reality

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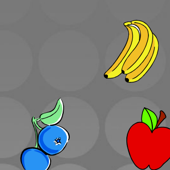
- Color as representation
  - Key color to real world
  - Iconographic vs. photographic
- Examples
  - Blue for water
  - Green for foliage
  - Red for apples, etc.



Illustrative Color

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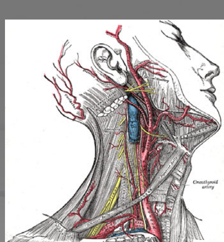

Gray's *Anatomy of the Human Body*
www.bartleby.com/107/illus520.html

Map of Point Reyes
www.nps.gov

Shape from Shading

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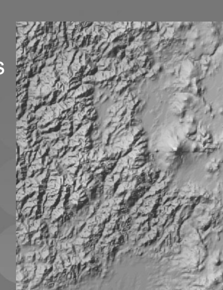
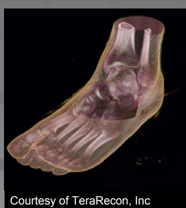
- Suggest 3D shape
  - Function only of lightness
  - Tufte: to measure
  - Also imitates reality
- Examples
  - Topo maps
  - Volumetric rendering
  - 3D graphics



National Park Service

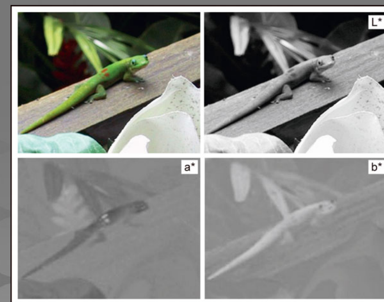


Courtesy of TeraRecon, Inc

Color helps define regions, but shape is defined by the shading

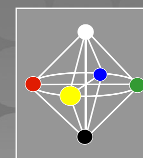
Courtesy of Resolution Sciences Inc.

Lightness vs. chroma



Basic image encoding technique

Give less spatial resolution to chroma



Legibility

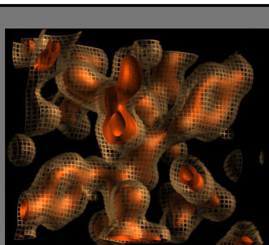
- Only lightness contrast creates edges
- Outlines, drop shadows add edge contrast

Contrast is important
Contrast is important
Contrast is important
Contrast is important
Contrast is important
Contrast is important
Contrast is important
Contrast is important
Contrast is important
Contrast is important

Drop Shadows
Drop Shadow

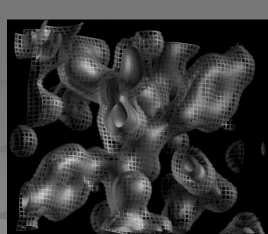
To Enliven or Decorate

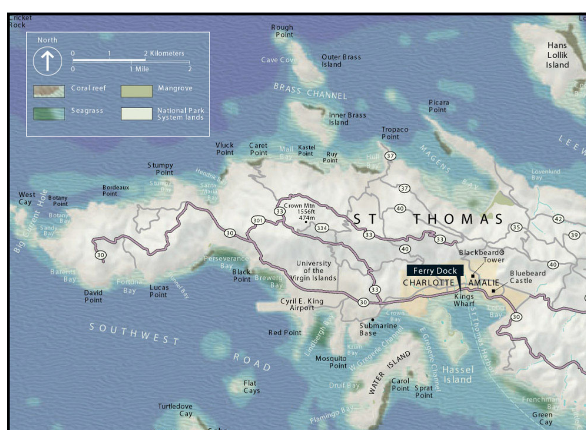
- Color as beauty
  - Aesthetic use of color
  - Emotional, personal
- Examples
  - Illustrations, maps
  - Illuminated manuscripts
  - Signs, logos
  - Computer “desktops”



Visualization of isoelectron density surfaces around molecules

Marc Levoy (1988)





Courtesy of the National Park Servic

Outline

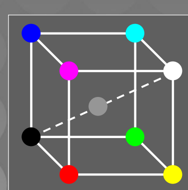
- Tufte's principles, examples
- Making color quantitative
  - RGB fundamentals
  - Psychophysical metrics (CIE XYZ)
  - Perceptual models
- Color appearance and design
- Making color robust

Color Spaces

- RGB fundamentals
- Psychophysical specifications
  - Color measurement
  - CIE tristimulus values (CIE XYZ)
- RGB to XYZ transformations
- Perceptual models
  - Munsell, CIELAB
- Color appearance and design models

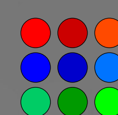
RGB Fundamentals

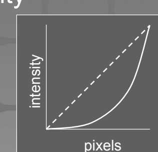
- Three primaries
  - RGB lights
  - Variable brightness (0..max)
- Characteristics
  - Primaries sum to white
  - Saturated colors on surface
  - Gray scale along diagonal
  - Cube bounds color gamut



Making RGB Quantitative

- Vector sum of three primaries
- Specify primary colors
  - Precise hue
  - Maximum brightness
- Map numbers (pixels) to intensity
  - Linear vs. non-linear encoding
  - Perceptual uniformity



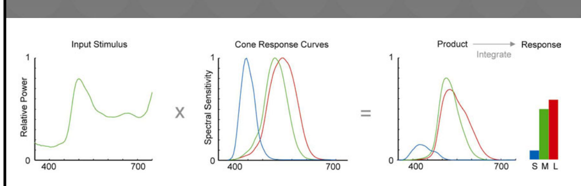


Specifying Color

- CIE Colorimetry
  - Encode spectrum (stimulus) as tristimulus values (CIE XYZ)
  - Two spectra that produce the same tristimulus values look the same
- Basis for color measurement
- Similar to cone function

Retinal Cones

- Short, medium and long (SML)
- Encode spectra as three values
- 3D vector space



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

CIE Standard Observer

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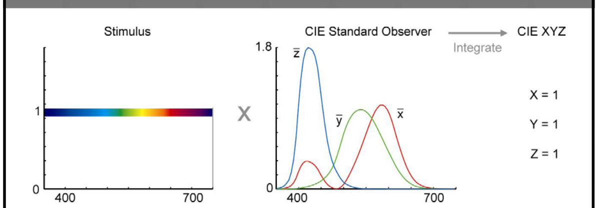
- CIE tristimulus values (XYZ)
- Positive for all visible colors
- 3D vector space



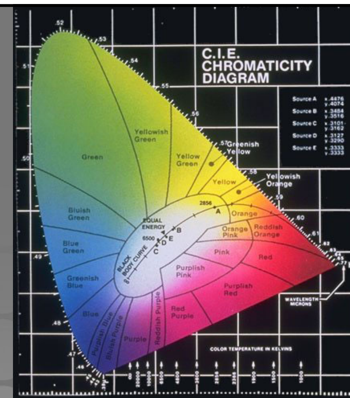
From *A Field Guide to Digital Color*, © A.K. Peters, 2003

Chromaticity Coordinates

Project X,Y,Z on the (X+Y+Z)=1 plane

$x = X/(X+Y+Z)$
$y = Y/(X+Y+Z)$
$z = Z/(X+Y+Z)$
$1 = x+y+z$

Separate *colorfulness* from *brightness*



Courtesy of PhotoResearch, Inc.

RGB Chromaticity

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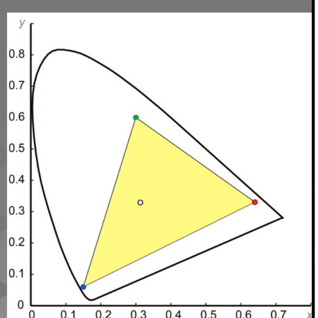
$R = X_R, Y_R, Z_R$
$G = X_G, Y_G, Z_G$
$B = X_B, Y_B, Z_B$

- R,G,B are points
- Gamut is a triangle
  - White/gray/black near center
  - Saturated colors on edges



RGB to XYZ to xy

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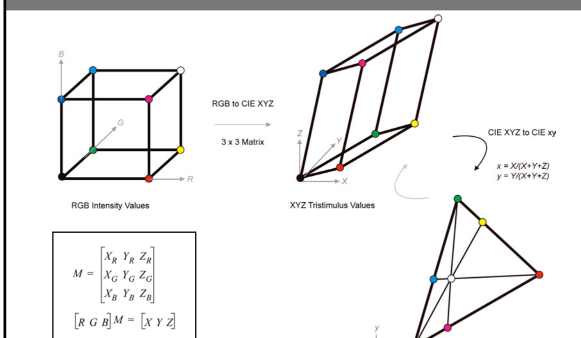

From *A Field Guide to Digital Color*, © A.K. Peters, 2003

Pixels to Intensity

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- RGB to XYZ assumes linear encoding
- Non-linear is more common
  - Perceptually uniform
  - More efficient
  - Encoding form: $I = p^{1/\gamma}$
- Display technology (CRT gamma)
- Image encodings (JPEG, MPEG, etc.)
- sRGB

Non-linear RGB to XYZ

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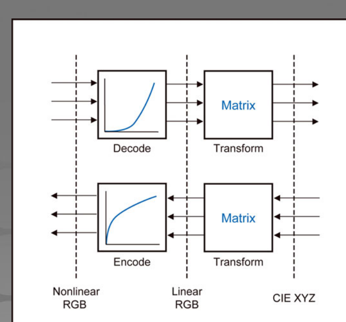
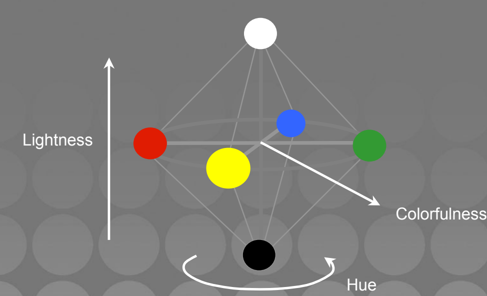


Value of RGB to XYZ Model

- Ties RGB color to visual psychophysics
- Ties RGB color to color measurement
- Foundation for "device-independent" color
  - Precise color and image specification
  - Display characterization
  - Foundation for color management systems

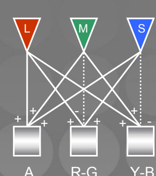
Perceptual Color Models



Unique black, white

Opponent Color

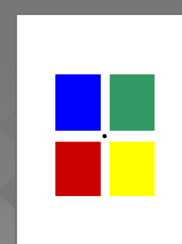
- Definition
  - Achromatic axis
  - R vs. G and B vs.Y axis
  - First-level processing
- History
  - Herring, 1878
  - Jameson & Hurvich (1955)



Fairchild, Figure 1-13

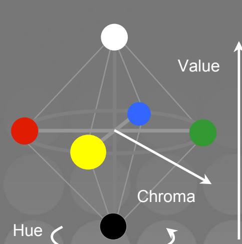
Support for Opponent Color

- Unique hues
  - —No reddish-green
- Afterimages
  - Red-green
  - Blue-yellow
- Color vision deficiencies
  - Red-green anomalies *
  - Blue-yellow anomalies



Munsell Color

- Hue, Value, Chroma
  - 5 R 5/10 (bright red)
  - N 8 (light gray)
- Perceptually uniform
- 10 steps each H, V, C
- Physical paint chips



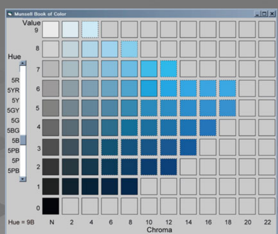
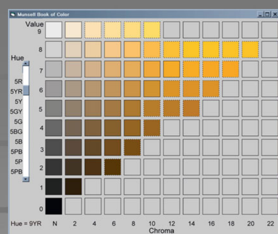
Munsell Renotation System maps between HVC and XYZ

Munsell Atlas

Courtesy Gretag-Macbeth

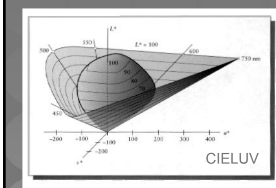
Interactive Munsell Tool

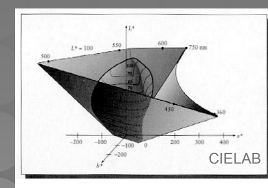
- From www.munsell.com

CIELAB and CIELUV

- Lightness (L*) plus two color axis
- Non-linear function of XYZ
- Needs XYZ for reference white





From Principles of Digital Image Synthesis by Andrew Glassner. SF: Morgan Kaufmann Publishers, Fig. 2.4 & 2.5, Page 63 & 64

CIELAB Equations

Equations for CIE 1976 L*, a*, b* (CIELAB)

$$L^* = 116\left[\left(\frac{Y}{Y_n}\right)^{1/3} - \frac{16}{116}\right]$$

$$a^* = 500\left[\left(\frac{X}{X_n}\right)^{1/3} - \left(\frac{Y}{Y_n}\right)^{1/3}\right]$$

$$b^* = 200\left[\left(\frac{Y}{Y_n}\right)^{1/3} - \left(\frac{Z}{Z_n}\right)^{1/3}\right]$$

X_n, Y_n, Z_n are the tristimulus values of the reference white.

If $(V/V_n) \le 0.008856$, where V is any of X, Y or Z, replace $\left(\frac{V}{V_n}\right)^{1/3}$ with $\left[7.787\left(\frac{V}{V_n}\right) + \frac{16}{116}\right]$ in the equations above.

Equations for Hue (h_{ab}) and Chroma (C_{ab}*)

$$h_{ab} = \arctan\left(\frac{b^*}{a^*}\right) \qquad C_{ab}^* = [a^{*2} + b^{*2}]^{1/2}$$

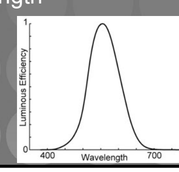
Ratio with reference white

Cube root except near zero

Polar coordinates for hue and chroma

Lightness Scales

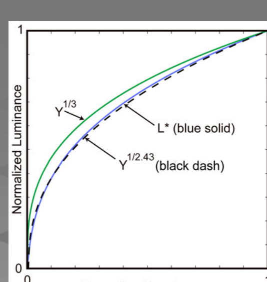
- Lightness, brightness, luminance, and L*
- Lightness is relative, brightness absolute
- Intensity is light power (cd/m^2)
- Luminance is perceived intensity
  - Luminance varies with wavelength
  - Luminous efficiency function
  - Equivalent to CIE Y



The L* Function

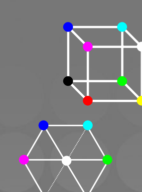
- Combination power + linear functions
- Not 1/3 power
- Best fit is 1/2.43

Similar issue in many other non-linear lightness specifications



Psuedo-Perceptual Models

- HLS, HSV, HSB
- NOT perceptual models
- Simple renotation of RGB
  - View along gray axis
  - See a hue hexagon
  - L or V is grayscale pixel value
- Cannot predict perceived lightness



L vs. Luminance, L*

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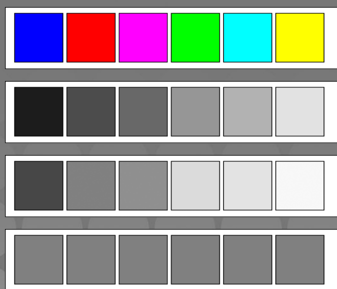


Uses for Perceptual Models

SIGGRAPH2004

- Compute color differences
- Predict legibility, color names
- "Intuitive" color selection
- Model for image compression
- Foundation for color appearance

Outline

SIGGRAPH2004

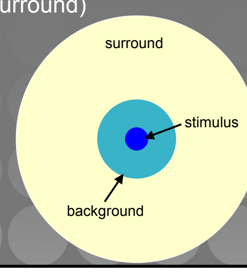
- Tufte's principles, examples
- Making color quantitative
- Color appearance & design
  - Color appearance
  - Color appearance models
  - Color design models
  - Color design principles
- Making color robust

Color Appearance

SIGGRAPH2004

- More than a single color
  - Adjacent colors (background)
  - Viewing environment (surround)
- Appearance effects
  - Adaptation
  - Simultaneous contrast
  - Spatial effects

Color Appearance Models
Mark Fairchild



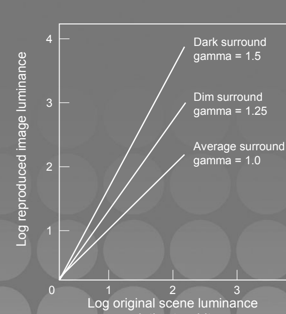
Light/Dark Adaptation

SIGGRAPH2004

- Adjust to overall brightness
  - 7 decades of dynamic range
  - 100:1 at any particular time
- Absolute illumination effects
  - Hunt effect
    Higher brightness increases colorfulness
  - Stevens effect
    Higher brightness increases contrast

Bartleson & Breneman

SIGGRAPH2004



Increase "gamma" of reproduced image as function of the viewing environment

Increases colorfulness and contrast

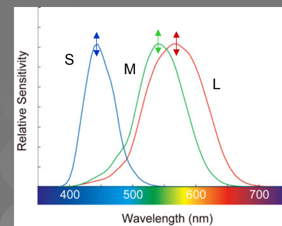
Standard practice in film and graphic arts

Chromatic Adaptation

- Change in illumination
- Cones “white balance”
  - Scale cone sensitivities
  - von Kries
- Also cognitive effects

From *Color Appearance Models*, fig 8-1

von Kries Adaptation



Adaptation by scaling the cone response curves

von Kries Model

- $L_1M_1S_1$ from $L_2M_2S_2$
- Scale by $\text{white}_2/\text{white}_1$
- Assumes full adaptation to new illumination

$$L_2 = (L_{white2}/L_{white1})L_1$$

$$M_2 = (M_{white2}/M_{white1})M_1$$

$$S_2 = (S_{white2}/S_{white1})S_1$$

LMS from XYZ

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.400 & 0.708 & -0.081 \\ -0.226 & 1.165 & 0.046 \\ 0.000 & 0.000 & 0.918 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

Linear transformation
various similar matrices in use

XYZ_2 from XYZ_1

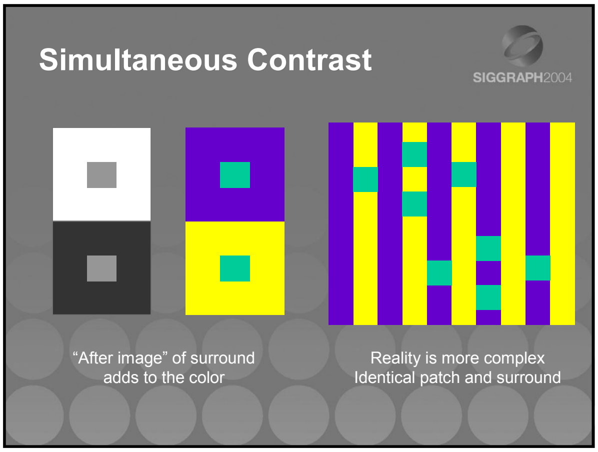
$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = M^{-1} \begin{bmatrix} L_{white2}/L_{white1} & 0.0 & 0.0 \\ 0.0 & M_{white2}/M_{white1} & 0.0 \\ 0.0 & 0.0 & S_{white2}/S_{white1} \end{bmatrix} M \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix}$$

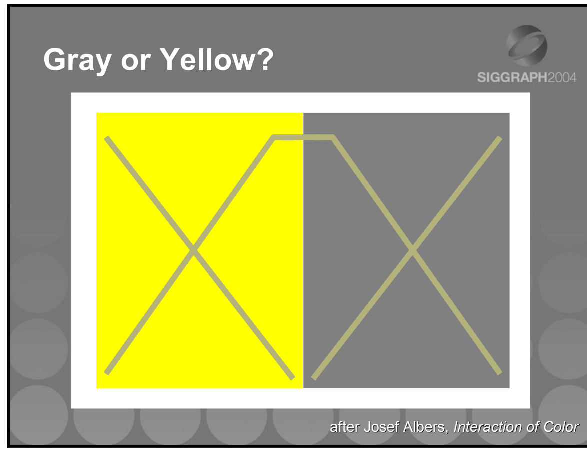
Where M is the transformation from XYZ to LMS

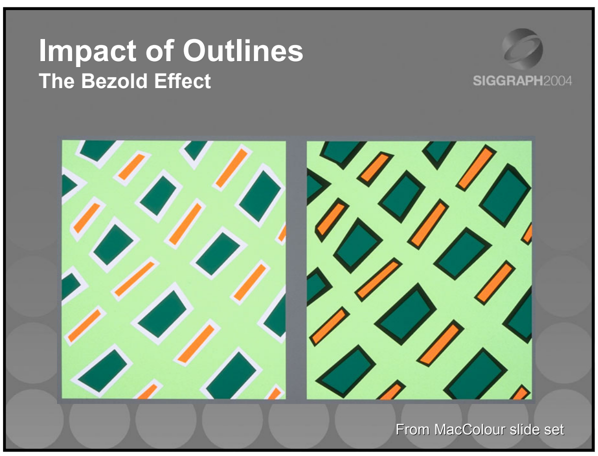
CIELAB: Wrong von Kries

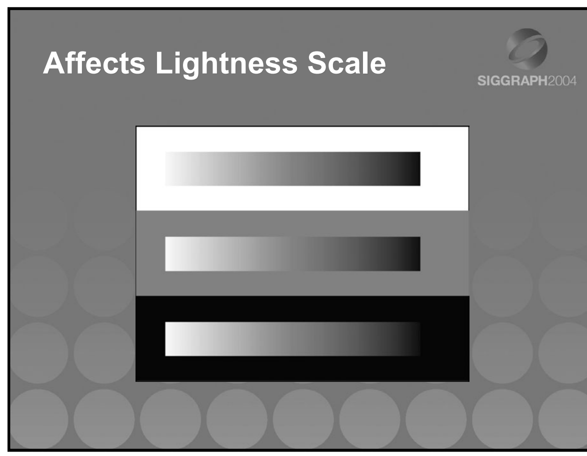
$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = \begin{bmatrix} X_{white2}/X_{white1} & 0.0 & 0.0 \\ 0.0 & Y_{white2}/Y_{white1} & 0.0 \\ 0.0 & 0.0 & Z_{white2}/Z_{white1} \end{bmatrix} \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix}$$

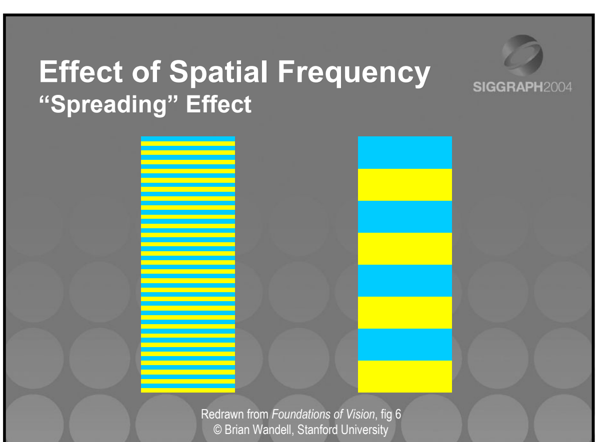
Scales XYZ, not cone response (LMS)

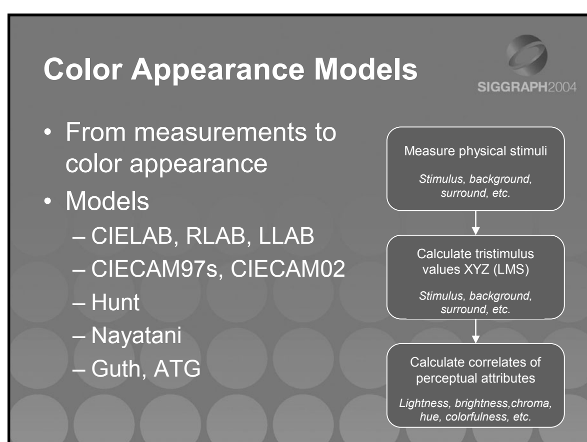

Simultaneous Contrast
SIGGRAPH2004
“After image” of surround
adds to the color
Reality is more complex
Identical patch and surround


Gray or Yellow?
SIGGRAPH2004
after Josef Albers, *Interaction of Color*

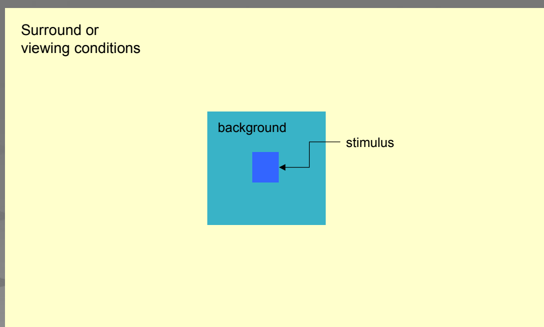

Impact of Outlines
The Bezold Effect
SIGGRAPH2004
From MacColour slide set


Affects Lightness Scale
SIGGRAPH2004


Effect of Spatial Frequency
“Spreading” Effect
SIGGRAPH2004
Redrawn from *Foundations of Vision*, fig 6
© Brian Wandell, Stanford University


Color Appearance Models
SIGGRAPH2004
• From measurements to color appearance
• Models
– CIELAB, RLAB, LLAB
– CIECAM97s, CIECAM02
– Hunt
– Nayatani
– Guth, ATG
Measure physical stimuli
Stimulus, background, surround, etc.
Calculate tristimulus values XYZ (LMS)
Stimulus, background, surround, etc.
Calculate correlates of perceptual attributes
Lightness, brightness,chroma, hue, colorfulness, etc.

Spatial Terminology



Color Terminology

Brightness—absolute, light emitting
Lightness—relative brightness

$$\text{Lightness} = \frac{\text{Brightness}}{\text{Brightness}_{\text{white}}}$$

Colorfulness—absolute
Chroma—relative to white
Saturation—relative to brightness

$$\text{Chroma} = \frac{\text{Colorfulness}}{\text{Brightness}_{\text{white}}}$$

$$\text{Saturation} = \frac{\text{Colorfulness}}{\text{Brightness}} = \frac{\text{Chroma}}{\text{Lightness}}$$

Requirements

CIE TC1-34, Testing Color Appearance Models

- Minimum requirements
  - Extension of CIE colorimetry
  - Predict lightness, chroma and hue
  - Chromatic adaptation transform (CAT)
- Also in CIECAM97s, CIECAM02
  - Absolute illumination
  - Background parameters
  - Surround (dark, dim or average)
  - Degree of adaptation (none to full)

CIELAB as CAM

- Meets minimum requirements
  - Based on CIE XYZ
  - Predicts hue, chroma and lightness
  - “Wrong von Kries” chromatic adaptation
- Problems
  - Inaccurate hue prediction for some colors
  - Fixed illuminant, background and surround

RLAB

- CIELAB plus
  - Modified von Kries chromatic adaptation
  - Includes effect of surround
  - Includes degree of adaptation
  - Readily invertible (XYZ from HCL)
- Designed at R.I.T. for imaging applications
- Fairchild and Berns

S-CIELAB

- Spatial extension to CIELAB
- Image comparison applications
- Zhang & Wandell

S-CIELAB

SIGGRAPH2004

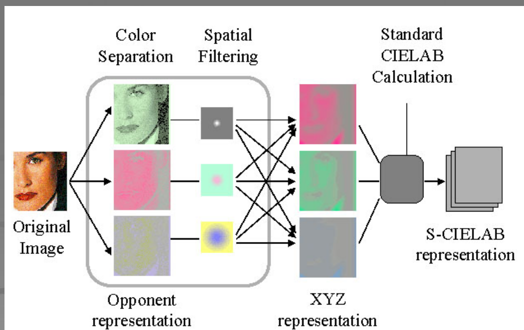


Image from Xhang & Wandell

CIECAM97s, CIECAM02

SIGGRAPH2004

- CIE Color Appearance Models
- Inputs
  - Tristimulus values of sample (XYZ)
    Tristimulus values of white (Xw Yw Z_w)
  - Relative luminance of background (Y_b)
  - Adapting field absolute luminance (L_A)

  Measure

  - Viewing condition factors
    - Surround (c)
    - Chromatic induction (N_c)
    - Lightness contrast (F_{LL})
    - Degree of adaptation (F)

    Select from table

Applications of CAMs

SIGGRAPH2004

- Color reproduction
  - Model adaptation across media
  - Aid in mapping out-of-gamut colors
- Model simultaneous contrast
  - Predict confusing color symbols (Brewer)
  - Compensate to give equal appearance on different backgrounds (DiCarlo & Sabataitis)
    http://ise.stanford.edu/class/psych221/projects/98/ciecam/Project.html

Aesthetic Color Models

- Hue (color wheel)
  - Red, yellow, blue (primary)
  - Orange, green, purple (secondary)
- Chroma (saturation)
  - Intensity or purity
  - Distance from gray

- Value (lightness)
- Similar to Munsell

Tints and Tones

SIGGRAPH2004

- Tone or shade
  - Hue + black
  - Decrease saturation and lightness

- Tint
  - Hue + white
  - Decrease saturation, increase lightness

Color Schemes

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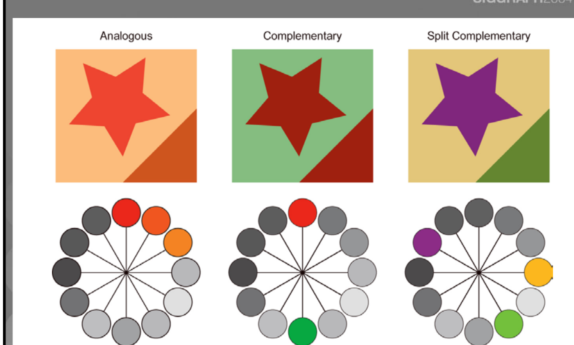
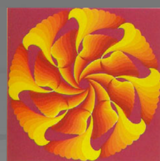


Color Harmony

Apply contrast and analogy to hue, chroma and value

Vary chroma



Analogous hues

Contrasting hues

Vary value

From Wong, *Principles of Color Design*, © 1997, John Wiley & Sons, Inc.

Color Design Principles

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- Use a limited hue palette
  - Limit color pop out, color grouping
  - Avoid clutter from too many competing colors
- Use neutral backgrounds
  - Control simultaneous contrast
  - Make it easy to control legibility
- Control value (lightness)

Control Value (Lightness)

SIGGRAPH2004

- Contrast vs. Analogy
  - Contrast in value creates emphasis
  - Equal value gives equal "weight"
- Establish contrast for edges, legibility
- Value defined by luminance
  - 5:1 contrast for legibility (ISO standard)
  - 3:1 minimum legibility
  - 10:1 recommended for small text

Principled Color Selection

SIGGRAPH2004

- Specially designed color spaces
  - Munsell, OSA, Ostwald
  - Any perceptual space
- Geometric interpretation of analogy, contrast and harmony
- Digital tools based on perceptual spaces
  - TekHVC (Taylor, et. al.)
  - Metapalette, Canon Color Advisor (Beretta)
  - Interactive Color Palette Tools (Meier et. al.)

Outline

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- Tufte's principles, examples
- Making color quantitative
- Color appearance & design
- Making color robust
  - Across viewers
  - Across systems and media
  - Color management systems

Accommodate the Viewer

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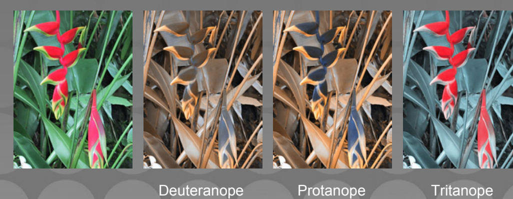
- Color vision deficiencies
  - Duplicate all information
  - Minimize red-green encoding
- Poor acuity
  - Increase contrast
  - Aging population
- Should "read" in gray only (luminance)

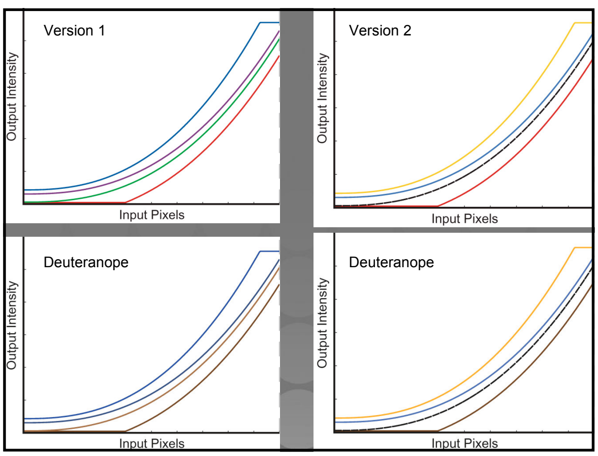
Color Vision Deficiencies

- Flaw in opponent processing
  - Red-green common (deuteranope, protanope)
  - Blue-yellow possible (tritanope)
  - Luminance channel almost "normal"
- Effect is 2D color vision model
  - Flatten color space
  - Can be simulated (Brettel et. al.)
  - Vischeck (www.vischeck.com)

Vischeck

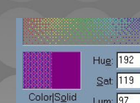
- Simulates color vision deficiencies
- Web service or Photoshop plug-in





Color-Deficient Media

- Monochrome media
  - Luminance contrast
  - Duplicate information
- Dither and halftone patterns
  - Texture and raggedness
  - Use solid colors
  - Default web colormaps



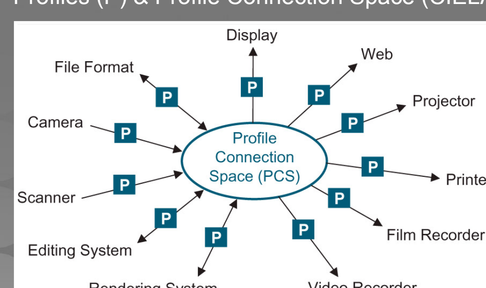
Netscape Navigator

Color Management

- Based on "Device-Independent" color
  - Characterize media (as in RGB to XYZ)
  - Characterize image encoding
  - Map (images) from one medium to another
- Color Management Systems
  - Profiles specify color (ICC standard)
  - CMS "engine" implements the transformations

Device-Independent Color

- Profiles (P) & Profile Connection Space (CIELAB)



Process

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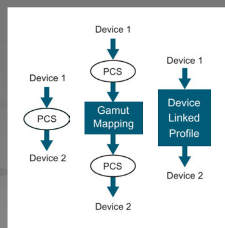
- Characterize devices, images
- Map through PCS
- Gamut mapping
  - Redefine black/white
  - Map out-of-gamut colors
  - Appearance transformation
- Scan-display-print focus



Monitor & Print in XYZ

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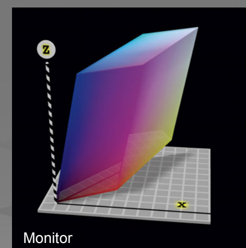

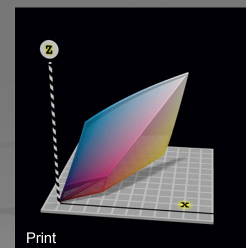

Images by Bruce Lindbloom

Monitor & Print in xyY

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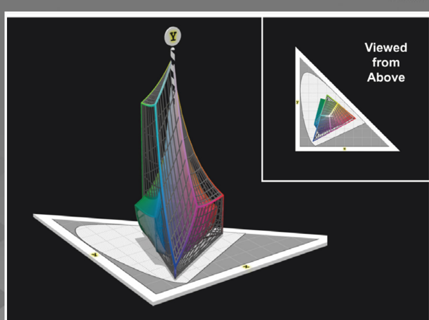

Images by Bruce Lindbloom

Monitor & Print in CIELAB

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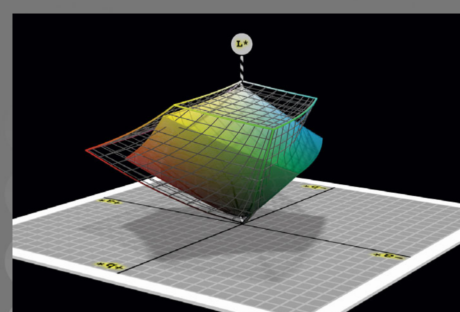

Image by Bruce Lindbloom

User-Center View

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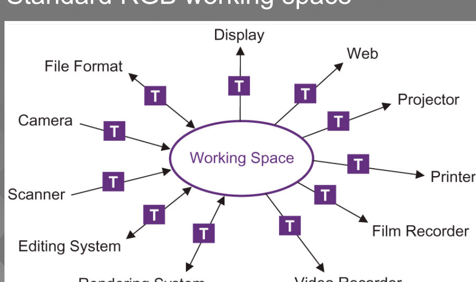
- Standard RGB working space



Considerations for RGB

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- Display-centered
  - Easy to see all colors
  - Non-linear RGB (like sRGB)
  - Missing some print and film colors
- Extended RGB
  - Covers print, film, and display
  - Non-linear RGB (like AdobeRGB)
  - Must gamut map to display

Common RGB Spaces

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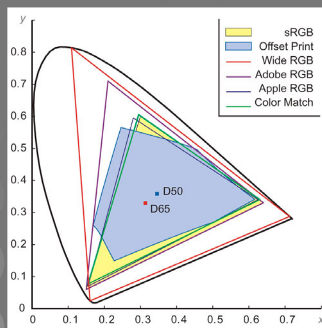
- All non-linear
- Gamma curve
  - 2.2 for PC
  - 1.8 for Mac



Computer Graphics View

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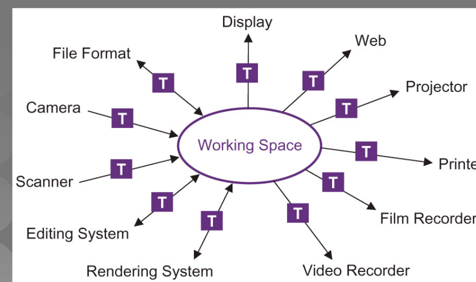
- Linear RGB rendering space



Color Management Made Easy

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- 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
- Control all (important) transformations

Characterize Your Display

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- Visual characterization
  - Display primaries from manufacturer
  - Visually set "gamma curve"
    - ColorSync or the Adobe Gamma Tool
  - CRT with 2.2 gamma = sRGB
  - Flat panels have different primaries
- Buy a meter and profiling software
  - Under $500 for display systems
  - www.colormall.com

Hooking to the CMS

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- Macintosh
  - Enable ColorSync
  - Set display, working space, etc.
- Adobe Tools
  - Built into Photoshop, Illustrator, etc.
  - Embedded in PSD, PDF, etc.
- Windows ICM
  - Piecewise implementation
  - Drivers, .icm files

Robust Color

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- Depends on quantitative color
  - RGB to XYZ to display
  - Color management can help
- Robust design
  - Reads well in gray scale
  - Avoids red-green coding
  - Duplicated by shape, texture, etc.

Summary

- Key technical components
  - Precisely specified RGB
  - Conversion to perceptual spaces
  - Characterized displays
- Robust, algorithmic color
  - Color labels
  - Color scales
  - Basic color design

Summary

- Color appearance models
  - Spatial component
  - “Characterized” environments
  - Currently driven by CMS applications
    - Images of natural scenes
    - Commercial graphic arts
  - Research opportunity for information display

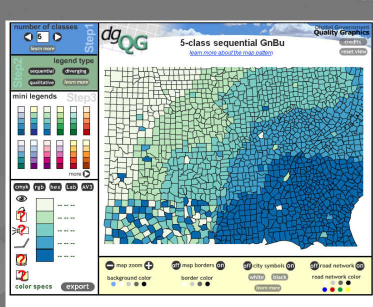
Extra Slides

- Color scales
- Color names

Color Scales

- Long history in graphics and visualization
  - Ware, Robertson et. al, Levkowitz et. al
  - Rheingans
- PRAVADA Color (IBM Research)
  - Rule-based system
  - Includes spatial frequency
- Cartography
  - Cynthia Brewer
  - ColorBrewer

Color Brewer



www.colorbrewer.org

Color Names

- Perceptual/linguistic fundamental
- Berlin & Kay, 1969
  - Linguistic specification
- Boynton
  - Perceptual foundations
  - Cross-cultural studies

Perceptual primaries

black
white
gray
red
green
blue
yellow
orange
purple
brown
pink

Commercially Used

- Color selection
  - Pantone Matching System®
  - Paint, fabrics, etc.
- NIST specification
  - *Color, Universal Language & Dictionary of Names,* Kelly & Judd, NBS 1976
    - Formal naming system
    - Map from commercial to standard
  - CGSD Corp. *Color Science Library*

Applications

- Computational models
  - Geometric locations perceptual space
  - Color-to-name agent (Lammens)
- Color names on displays
  - Color names on CRTs (Post, Shinoda…)
  - Web experiment (Moroney)
- Gamut mapping
  - Luo, MacDonald, et. al

Applications

- Selection by name
  - Berk, Brownston & Kaufman, 1982
  - Meier, et. al. 2003
- Image recoloring
  - Saito, et. al.
- Labels in visualization
  - D'Zmura, Cowan (pop out conditions)
  - Healey & Booth