

# Color in Information Display

## Principles, Perception, and Models

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Course 20  
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### **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](http://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](http://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 Trennisch 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.

Wyszecki 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. Wyszecki 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](http://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](http://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 6<sup>th</sup> 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](http://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](http://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.