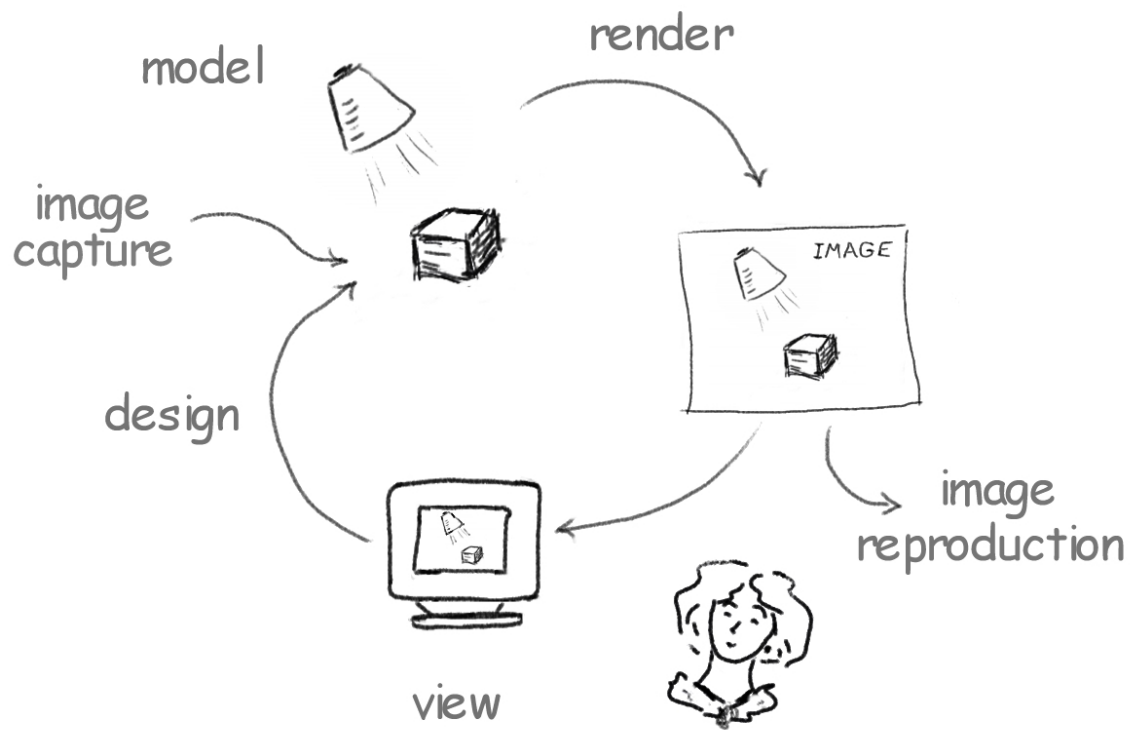


A Survey of Color for Computer Graphics

Maureen C. Stone
StoneSoup Consulting

Course 4
SIGGRAPH 2001
August 12, 2001



Description

This course will survey color disciplines relevant to Computer Graphics ranging from color vision to color design. Participants should leave with a clear overview of the world of digital color, plus pointers to in-depth references on a wide range of color topics. For each topic, a brief overview and pointers to further information will be provided. For most topics, I will suggest a standard reference book or two, augmented by published articles as needed. The course should be of value both to those seeking an introduction to color in computer graphics and to those knowledgeable in some aspects of color who wish to get a broader view of the field.

Presenter

Maureen Stone is an independent consultant working in the areas of digital color, large format displays, web graphics, interaction and design. Before founding StoneSoup Consulting, she spent 20 years at the Xerox Palo Alto Research Center where she attained the position of Principal Scientist. 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 first presented this survey course at SIGGRAPH '99. She has a BS and MS in Electrical Engineering from the University of Illinois, and a MS in Computer Science from Caltech.

Contact Information

Maureen Stone
StoneSoup Consulting
650-559-9280

<http://www.stonesc.com>
stone@stonesc.com

Schedule

0:00-0:30	Color Vision and Appearance
0:30-1:00	Color Reproduction and Management
1:00-1:30	Color in Rendered Graphics
1:30-2:00	Color Selection and Design

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Introduction

The goal of this course is to provide a broad survey of the color disciplines that relate to computer graphics. Color is an enormous field, with applications in almost every area of life. The taxonomy I present is designed to match common applications in graphics. It is, by definition, incomplete and superficial. Therefore, I base my presentation on standard texts and references in the field of color as much as possible. My hope is that after taking this course, you will know what there is to learn, and where to learn about it. If some of the fundamental principles can be learned just from the presentation, that would be great also.

These notes are a description of the material that will be presented in the course. They include an extensive, annotated bibliography plus copies of the slides. Because of the way the bibliography is structured and annotated, I did not feel that it was necessary to cite the references from the notes text.

The course is divided into three areas: vision, reproduction and synthesis. The vision section provides the foundations for understanding color and its applications. The reproduction section discusses color media and color management. The synthesis section is split into computer graphics rendering, color selection and color design.

Color Vision

In this section, I will discuss basic color vision, colorimetry and color appearance. The reference I use for color vision is Brian Wandell's *Foundations of Vision*, which is structured in three parts: Encoding, representation¹ and response. What I call "basic color vision" is essentially the encoding part of his taxonomy. Colorimetry uses these principles to measure color. Wyszecki and Stiles *Color Science* is considered the standard reference for colorimetry, though most of what is presented here can be found in almost any color text. Color appearance is the response of the visual system to color. Mark Fairchild's *Color Appearance Models* is a recent book on color appearance that includes both a complete description of color appearance as it is currently understood, and a survey of computation models that are being developed to address this complex topic.

Basics

Light enters the eye as spectrum of colors, distributed by wavelength. This *spectral distribution function* impinges on the retina in the back of the eye and is absorbed by the *cones*. Human beings have three types of cones, which respond to different wavelengths of light. These are called either long, medium and short wavelength cones, or, correspondingly, red, green and blue cones. Each cone absorbs light and sends a signal to the brain. That is, the spectrum of light is encoded into three values that correspond to the amount of light absorbed by each type of cone. This is the principle of *trichromacy*—human vision is 3 dimensional.

It should be clear that the actual distribution of the spectrum is only indirectly "seen" by

¹ Brian's representation section focuses on the visual pathways in the brain—I will not address these issues at all.

the eye. The response of each cone can be encoded as a function of wavelength (the *spectral response curve* for the cone). Multiplying the spectrum by such a function and integrating produces the signal that is sent from the eye to the brain. Different spectra can produce the same signal, and as such, will “look the same.” This principle is called *metamerism*.

The principle of metamerism underlies all color reproduction technologies. Instead of reproducing the spectral stimulus, they create an equivalent response, or *metameric match* by mixing primary colors in a controlled way.

Trichromacy and metamerism can also be applied to the problem of measuring color. It is important in many industries to be able to measure colored materials. If we can create an instrument that responds in the same way as the human eye, we can have an impartial observer to define when colors match. From the discussion above, it seems obvious to fit an instrument with filters and sensors that behave like the cones. However, the precise definition of the cone response was not known until very recently. The science of color measurement is much older, and is based on experiments involving matching colors with sets of three primary lights. This is called *colorimetry*.

Colorimetry

The color matching experiments that underlie colorimetry are constructed as follows. Choose three primary lights (call them red, green and blue). Then, take a set of reference colors such as the monochromatic colors of the spectrum, or those generated by filtering a white light. For any set of three independent primaries, you can match any other color. Period. The only requirement is that you allow the primaries to go negative. In a physical matching experiment, this means that you shine the “negative” primary on the sample to be matched. This is a remarkably useful result. It means we can create a representation for color based on three primary lights. Any color can be defined as a set of three numbers that correspond to the power of the primaries. These three numbers are called the *tristimulus values* for the color.

How do we know what primary values match a particular color? Clearly we cannot perform the color matching experiment on all possible spectra. The answer is to use the fact that colored light is additive. A spectrum can be constructed by adding a number of monochromatic lights together. This seems obvious, but what is less obvious is that the amount of the primaries needed to match colored light is also additive. Specifically, let the primaries be R, G and B. Let the spectrum be S. If RGB_1 matches S_1 , and RGB_2 matches S_2 , then RGB_1+RGB_2 will match S_1+S_2 . This principle was first formalized by Grassman, it is called *Grassman’s law*.

To define the primaries for an arbitrary color, we use Grassman’s law to construct a set of *color matching functions* for the primaries. We perform the color matching experiment on each of the monochromatic spectral colors (sampled every 2 nm, for example). We use the result to create a set of three functions, one for each primary. To determine the amount of the primaries needed to match a particular spectrum, multiply the spectrum by the color matching functions and integrate. Three multiplications and three integrations, and you have the match. As all the functions described are sampled, this process is quite simple to implement.

What if we decide to use a different set of primaries? Do we have to repeat the color matching experiments? Most wonderfully, the answer is no, we can compute the color matching functions for the new set of primaries from the old ones. All we need to know is the definition of the new primaries in terms of the old ones. For those of you familiar with linear algebra, this is simply a change of basis, and can be accomplished for a three dimensional system with a 3×3 transformation matrix. You apply this matrix to each of the samples in the color matching functions in turn to create the color matching functions for the new set of primaries.

The color matching functions are remarkably like the spectral response curves for the cones. Multiply each by the viewed spectrum, and integrate to get an encoding into three numbers. Are these two types of curves related? The answer is yes, that the cone response, too, is linearly related to the set of color matching functions. This result was only recently demonstrated by Bayer, Nunn and Schnapf in 1987.

In 1931, the *Commission Internationale de l'Eclairage (CIE)* standardized a set of primaries and color matching functions that are the basis for most color measurement instruments used today. They transformed a set of color matching functions measured by Stiles and Burch to create a set of curves that were more convenient to use. This set is positive throughout the entire visible spectrum, and one of the curves can be used to compute the perceived brightness of the measured color. The CIE standard tristimulus values are notated X, Y and Z. They are often reduced to two dimensions by projecting them onto the $X+Y+Z=1$ plane, creating the CIE *chromaticity diagram* with its corresponding *chromaticity coordinates*, x and y .

Colored objects can be described as having spectral reflectance functions that selectively reflect and absorb light shined on them. A “red” object reflects the red wavelengths of light and absorbs the rest. Colorimetry can be applied directly to the light reflected from objects. It is sometimes applied to the reflectance spectrum (measured by reflecting a known light off of a sample) as well. However, this spectrum cannot be perceived directly. What is viewed is always a function of both the object and the light.

Some of the basic concepts of vision are demonstrated in the *Color Playground*, created at Brown University (<http://www.cs.brown.edu/exploratory/ColorWeb/>). A copy of these demonstrations are included in the CDROM version of these notes. They demonstrate 1) trichromacy 2) reflectance and 3) metamerism.

Color Appearance

The models used in colorimetry are remarkably simple. Color is a three-dimensional, linear system that can even be encoded in instruments. However, the truth about the perception of color is much more complex. Color matching as described above only works for individual colors viewed under simple, controlled circumstances. Its definition is based on the simple perception of colored light. In the real world, we see complex arrangements of colors. These colors interact in ways that defy the simple model presented by colorimetry.

In the slides is a classic photograph taken by John McCann. In it, two standard color

charts are seen, one in the sun and one in the shade. The difference in lighting is such that the measured intensity of the black patch in the sun is exactly the same as the white patch in the shade. That is, two instruments would assign them the same color, but they clearly look black and white in context. A similar situation exists with the gray step wedge, which lies across the shadow boundary. In spite of the fact that the intensity of the light reflected from the patches actually increases in the sunlight, it appears to show a monotonically decreasing set of gray steps.

Why the appearance of colors in the real world is so different than the simple models defined by the retina is a combination of perceptual and cognitive effects. The perceptual effects are created by the encoding and processing in the brain of the original retinal signals, which is more complex than the simple RGB encoding described so far. Cognitive effects are based on our knowledge of how objects and lights behave in the world.

If you ask people to describe a color, they do not normally speak in terms of its red, green and blue components. They will typically name a hue, such as red, purple, orange or pink. They may describe it as being light or dark. Or, they may call it vivid, colorful, muted, or grayish. This perceptual organization of color is used to define most “intuitive” color spaces.

One of the best known perceptually organized color space is the Munsell space, which is roughly spherical in shape. Colors are organized with a vertical lightness axis (called value), hue arranged around the circumference, and chroma (or saturation) defined radially. Each step in the color space is of equal perceptual distance. That is, the difference between two colors is uniform throughout the space. This is not true of the CIE tristimulus space. The original Munsell definition was created with hand-painted color chips, and you can still buy *The Munsell Book of Color* from the Munsell Color division of Gretag-Macbeth (www.munsell.com). The Munsell chip set has also been defined with respect to the CIE tristimulus space.

There are two uniform color spaces defined by the CIE for the measurement of color differences. Called CIELAB and CIELUV, they are non-linear transformations of the CIE tristimulus values. Like the Munsell space, they are perceptually uniform. They have been defined such that a unit step in the space is considered a “just noticeable difference” or JND. Each space has a lightness axis (L^*) and two opponent color axis (CIELAB = $L^*a^*b^*$ and CIELUV = $L^*u^*v^*$). The equations that define the spaces include the tristimulus values for a reference white. This is necessary to create a single lightness axis.

This perceptual organization of color reflects the first level of processing applied to the cone response, called the *opponent color model*. In this model, the RGB values from the retina are encoded as lightness plus a red-green and a blue-yellow color difference axis. This organization of color can be seen in the afterimages produced by staring at brightly colored patches. Stare at a red color, then look at a white surface—you will see a greenish afterimage caused by saturating the red-green opponent channel. You can create similar effects with blue-yellow patches, and with light-dark ones.

The opponent color model also well describes the common forms of color vision deficiencies. While these are usually caused because one type of cone in the retina is either missing or weak, they are most easily described in opponent terms. The most common problems are anomalies in the red-green opponent channel, where either the ability to see

red or to see green is impaired. This type of deficiency appears in approximately 10% of men. A much smaller percentage (1-2%) are weaknesses in the blue-yellow channel, with very few people actually “color blind,” or unable to see any hues at all. While most color vision problems are genetic, they can also appear as a side-effect of medication or illness.

Opponent color theory was first proposed by Hering, in 1878, but was not accepted until Dorthea Jameson and Leo Hurvich performed controlled experiments in 1955 that verified the theory. It is now accepted as the first-level processing of the color vision signal after the cone response. Leo Hurvich has written a textbook, *Color Vision*, that is based on this theory. It is also the best technical reference I have found for the modalities of color vision deficiencies.

Color appearance phenomenon are caused by the relationship between colors, by adaptation and by cognitive effects based on our knowledge about lights and objects in the real world. *Simultaneous contrast* describes the influence of surrounding colors on the perception of a color. There are several simultaneous contrast examples in the slides. The simplest model for simultaneous contrast is that the afterimage of the surrounding color is added into the perception of the surrounded color. Therefore, a gray patch on a dark background looks lighter (add white) than a gray patch on a white background (add black). However, the real answer is more complex. In the slides are a set of colored patches on a background of alternating colored bars. Which bar the patch appears on changes its appearance, even though the actual surround is identical. Clearly the cognitive effect, in which we see a patch as being “on” a particular colored bar, is contributing in this example.

Even a thin outline of a different color can make a big difference in the appearance of a colored region. The slide labeled the “Bezold Effect” demonstrates this. The only difference between the two patterns is the color of the outlines; white in one case and black in the other. But, the overall difference in appearance is quite dramatic. This effect was named for a 19th century rug designer, who was able to reuse his designs by this simple alteration.

Size, or spatial frequency, has a strong impact on the perception of a color. The higher the spatial frequency, the less saturated the color. This is why the paint on the sample chip looks less vivid than it does on the wall. In the slide, the two colors really are identical.

Human vision is very adaptable. We are capable of seeing in both very dim and very bright light. When we move from bright to dim lighting, or vice versa, we can feel our visual system adapt. Think of this as a gain control on the visual system. For dim lighting, we turn up the sensitivity. For bright lights, we need to damp it. These phenomena are called *dark adaptation* and *light adaptation*, respectively. In many cases, it is valid to assume that color appearance is relative to the current black/white levels, and is not effected by the absolute luminance. However, increasing luminance can produces a measurable increase in colorfulness (Hunt Effect) and contrast (Stevens Effect).

Chromatic adaptation describes the visual system’s ability to adapt to the color of the light illuminating the scene. Most color is created by shining light off of objects. While the reflected spectrum can be measured with colorimetric instruments, changing the light will change the measured color, sometimes dramatically. But, as we view the world, we

don't generally perceive objects changing color as the light shifts. Think of it as an automatic white-balancing function for the visual system. That is, the gain controls for the three cones are adjusted separately. Modeling chromatic adaptation is very important for the accurate reproduction of images, which will be discussed in the color media and management part of this tutorial.

The cone response curves physically adapt to the color of the light source. This idea was first proposed by von Kries in 1902. von Kries did not present a mathematical model, but simply proposed the concept that the cones could independently adapt. Modern interpretations of von Kries are expressed in terms of a scalar value, k , that is the inverse of the maximum response for each cone, typically the response for white.

A color appearance model converts from measured values (such as the tristimulus values of the sample and its surrounding color, the overall illumination level, etc.) to correlates of perceptual attributes of color, including hue, chroma, lightness, brightness, etc. All color appearance models include a way to compensate for adaptation to different lighting conditions. Color appearance models are important for digital imaging applications, and are under active development. The CIE has codified a model, called CIECAM97s. Other models include CIELAB (minimal), RLAB and LLAB (improved CIELAB), Hunt, Nayatani, Guth and ATG. Mark Fairchild's book is an excellent reference on this topic.

Color Reproduction and Management

Color reproduction focuses on the reproduction of colored images. It has been defined by the different technologies used in the traditional color reproduction industries: television, printing and photography. The best reference for this topic I know is Hunt's *Reproduction of Colour*. First published in 1957, the fifth edition was published in 1996. Dr. Hunt is still active in the field, working with the *Colour & Imaging Institute* at the University of Derby in England. Gary Field has two newer books on the topic, *Color and Its Reproduction, 2nd Edition* and *Principles of Color Reproduction*, an update of John Yule's classic book on printing, which has long been out of print.

Traditionally, each color reproduction industry had its own separate technologies and skills. With the coming of digital imaging systems, these industries are being integrated, both with computing and with each other. It is not unusual to find a graphic arts business equipped with digital scanners, printers, film recorders, video cameras and video editing stations. The representation and management of color images in digital form was hinted at in the late 70's, demonstrated in the early to late '80s, and is now an established commercial domain. *Color management systems* are now part of every high-end color reproduction application, and are becoming more common for simple desktop publishing users. Giorgianni and Madden, both from Kodak, have written a book called *Digital Color Management* that is an excellent reference for this topic.

The color reproduction industries, photography, printing and television, were traditionally focused on the reproduction of natural scenes. Such reproductions are inherently approximations, as no technology can reproduce the full range of colors visible in nature. Each industry tuned its process to provide the best approximation of the real world on its medium. Now, there is an increasing focus on cross-media reproduction and the integration of purely digital content as well as images of nature. This means that color

reproduction is becoming less about specific technologies and more about integrating all of them.

Color reproduction

The process of color reproduction involves capturing the light reflected from or emitted by an original, then reproducing it for viewing. The goal is to make the reproduction look as much like the original as possible. That is, viewing the reproduction should be as similar as possible to viewing the original scene, within the limitations of the medium. All media can only reproduce a fraction of the human color vision experience, so all reproductions are approximations. The definition of the ideal reproduction ultimately becomes one of preference and context, though there is substantial technical and craft information about creating good reproductions. As well as the books mentioned in the introduction to this section, there are the publications of the Society for Imaging Sciences & Technology (IS&T) and those of the Graphic Arts Technical Foundation (GATF).

From our study of color matching, we know we can encode the colors reflected from a scene as three numbers that represent roughly the red, green and blue components of the colors seen. *Image capture*, therefore, is the process of capturing and encoding these values for every point across the image. These are the familiar image pixels used in digital representations of images. The separate red, green and blue images are sometimes called *color separations*. These separations are reproduced by mixing primary colors for the output medium. For light-producing media such as monitors or digital projectors, the primaries are red, green and blue light. This is called *additive reproduction*. For subtractive media such as film and print, the process involves subtracting the red, green and blue components from a white light using layers of colored filters, or *subtractive reproduction*. The primaries for the subtractive media are named after the color of the filters: cyan, magenta and yellow.

Good image reproduction maintains the appearance of the original. As in color appearance models, control of *tone reproduction*, which is the reproduction of the overall brightness and contrast (the achromatic axis) is separated from the problem of adjusting hue and saturation. Tone reproduction is simpler to model than color reproduction as it involves only one dimension and can easily be implemented with table lookup in digital systems. Many image reproduction problems can be satisfactorily solved simply by controlling the tone reproduction. In traditional image reproduction industries, careful tone reproduction was augmented with color correction, a step that simply tried to adjust the primary input colors to better match the output media. This was usually achieved by processing each separation independently, as can be done with the RGB (or CMYK) curves in tools like Adobe's Photoshop.

Color management systems provide a more general mechanism for matching colors based on measurements of the *gamut*, or set of all possible colors that can be produced by any output device (printer, monitor, etc.) Generating such a specification is called *characterizing* the device. The characterization data is encoded in a *device profile* that represents the color reproduction characteristic for the device. Modern color management systems use a colorspace based on the CIE standards for this purpose. Most commercial systems use CIELAB, though some also support the use of the standard CIE XYZ tristimulus values. Future systems will be based on appearance models such as CIECAM97s.

Image capture

To perform image capture, the scene is viewed through red, green and blue filters. If the filters represent color matching functions, the red, green and blue values would be tristimulus values. Typically, however, image capture filters are not color matching functions (or *colorimetric filters*). Such filters are expensive to make and inefficient to use because they absorb a great deal of the incoming light. More often, the filters are tuned to match the expected inputs and outputs. Because they are not true color matching functions, they may mis-code some colors. That is, two colors that look different to a human viewer may encode to the same RGB triple, and vice versa. However, substantial engineering effort has been spent to minimize these effects.

Input devices must be characterized for use with color management systems. However, the characterization can only be general if the device uses colorimetric filters. Otherwise, the characterization depends on the input spectra used in the measurements. For example, a scanner could be characterized by scanning a set of colored patches with known CIELAB values and making a correspondence between the resulting RGB pixels and the CIELAB values. Other values could be interpolated from this set, and the inverse transformation generated by inverting the input table. However, patches of a different material (paint vs. a photographic print, for example) that have the same CIELAB value might produce different RGB values in the scanner. Commercially, most scanned material is photographic prints or other printed materials of a standard form so that there are a limited number of characterizations needed in practice.

Additive color systems

Additive color systems reproduce the red, green and blue parts of the image by adding together red, green and blue lights. Such systems include monitors, liquid crystal displays (LCD) and digital projectors. The traditional additive color reproduction industry is television, though scanned graphics displayed on a monitor may be more familiar to this audience. Charles Poynton's book on *Digital Video* is a good reference for video and television technology. Lindsay Macdonald and Anthony Lowe have edited a good general reference on *Display Systems* for those who want more detail about specific display technologies. The Society for Information Display's (www.sid.org) conferences and publications are the standard venue for research in display technology.

To achieve a good additive reproduction system we need to match the color and the relative brightness of the input and output primaries. Let's talk first about intensity, or brightness. The *intensity transfer function* (ITF) is the curve that maps input values (pixels or voltages) to intensity (viewed light). A monitor's ITF is a non-linear, power function called a *gamma function*, which is defined primarily by the physics of the electron beam that excites the phosphors. Most modern monitors are manufactured such that they have identical gamma functions. The shape of the function can be modified, however, simply by changing the contrast and brightness adjustments on the display.

In the slides is a diagram that describes the ITF's for the television pipeline. The linear intensity values reflected from the original scene are non-linearly encoded in the camera. This both optimizes the use of pixel values by companding or compressing the intensities, and creates values that can be fed directly into the television electronics. The original de-

sign was to make this encoding is exactly the inverse of the gamma function of the receiving monitor. However, studies by Bartleson and Breneman in the 70's demonstrated that a slightly non-linear reproduction was perceptually more accurate because of the normally dim viewing environment for television. Therefore, while a typical monitor has a gamma function of 2.5, the camera encodes to the inverse of 2.2.

For monitors, the color of its primaries is defined by the phosphors used. Most modern monitors have a similar set of primary colors. Liquid crystal displays, however use colored filters and a backlight to define their pixels. Standards for these are still evolving. Specifically, there is a tension between the desire for bright saturated colors (bright, high-powered backlight, intensely colored filters) and battery life (dimmer, low-powered backlight and thinner, less saturated filters). The ITF for a liquid crystal display is not inherently a gamma curve, though some manufacturers apply one artificially for compatibility with monitors and video.

Digital projectors are another additive color device that are becoming common. A projector contains an imaging element such as a small LCD or an array of micro-mirrors (DMD) that modulates the light from a high-intensity light bulb. Most LCD projectors and the larger DMD projectors contain 3 imaging elements and a dichroic mirror that splits the white light from the bulb into its red, green and blue components. These are recombined and displayed simultaneously. The smallest projectors, however, use a single imaging element and a color wheel of filters, so the separations are displayed sequentially. The DMD projectors based on Digital Light Processing (DLP) from Texas Instruments can weigh as little as 3 lbs and still produce a bright, crisp, image. Their colorwheel includes a clear filter that is used to add white to the brighter colors. This increases the dynamic range of the system, but makes it more complex to characterize. The native ITF for a projector is defined by the imaging element. DMD elements actually pulse encode the grayscale, making them naturally linear. However, like flat panel displays, most projectors contain image processing hardware that induces a gamma curve compatible with monitors and video.

There is are diagrams in the slides that plot the typical monitor gamut (yellow solid triangle) with several different LCD gamuts and a couple of digital projector gamuts. Traditionally RGB reproduction systems assume a common RGB because most displays were monitors. Now, this is no longer true. However, it is straightforward to transform from one RGB system to another by inserting a matrix multiplication in the output pipeline. This can be implemented in special purpose hardware, as in video systems. Modern graphics cards, such as the Nvidia G-Force 2 (www.nvidia.com), provide a programmable function that can be applied to this problem.

Characterization of additive systems is fairly easy because there is a linear transformation between RGB intensity values and CIE tristimulus values. This transformation can be defined by measuring the red, green and blue primaries. For most display technologies, this creates a 3x3 matrix that transforms from RGB intensity to XYZ. For projection displays, it is necessary to include a translate component to compensate for the high black level of these devices. This results in a 4x4 homogeneous transformation matrix. Note that the transform must be applied after the ITF is applied, not to the pixel values directly. The DLP projectors with the clear filter in the colorwheel, however, are not so simply characterized.

Subtractive color systems

Subtractive color systems filter the red, green and blue components of the image from white light. To do this, they use colored filters that in theory modulate only the red, green and blue components of the spectrum. The filter that passes green and blue but modulates red appears cyan. Similarly the green-modulating filter appears a purplish-red called magenta, and the blue-modulating filter is yellow. Therefore, the primaries of a subtractive reproduction system are said to be cyan, magenta and yellow. In printing, black ink is added as well, to improve the contrast.

The advantage of subtractive color systems is that they use a single, white light source instead of three colored ones. Furthermore, for reflection prints, this light is simply the light in the room. While flat-panel displays are getting thinner and lighter, it is hard to imagine they will ever be as light, convenient and inexpensive as a sheet of paper.

In a reflection print, the colored ink or film forms layers on a white background. Light passes through the layers and is reflected back to the viewer. Compared to light emitted from a display, or even light passing through a colored transparency (like a 35mm slide), prints are low-contrast and desaturated. This is caused by scattering as the light passes through the colored layers twice. Reduced scattering is why colored prints look more vivid on smooth, coated papers than on matte ones.

The cyan, magenta and yellow filters created with printing inks are far from the ideal filters described above. That is, the cyan filter, which should only modulate the red part of the spectrum, also affects the green part. Similarly, magenta modulates both red and blue as well as green. This means that there is interaction, or *cross-talk* between the filters. They do not function as independent primaries in the same way that RGB lights do. The result is that it is difficult to predict what color a particular combination of inks can produce. Whereas RGB systems are linear, CMY systems are not.

In printing, black ink is often added to the cyan, magenta and yellow separations to improve contrast and to reduce the amount of ink spread on the paper. In theory, black and gray colors can be created by combining equal amounts of cyan, magenta and yellow. In practice, such a combination will often produce brown or olive green. *Gray balancing* is the process of determining the correct mixture of primaries to create a gray color. The darkest color produced by mixing the three primaries, black, can be made darker by printing black ink on top of the three primaries. It is also possible to replace some of the colored ink with black, though once again, there is not a simple, linear relationship that predicts how much black ink is needed to replace a specific blend of CMY. The process of substituting black for the primaries in the darker colors is called *gray component replacement*, or GCR.

Another topic of significance for printing is *halftoning*, or the process of converting intensity into dot patterns on the paper. Most printing systems are binary—ink either is printed or not. To get the appearance of gray, the ink is printed as high-resolution patterns called *halftone patterns*. Originally made for mechanical printers by using a special filter and films, these patterns are now digitally produced on ultra-high resolution film recorders. The design and implementation of the halftone pattern has an important effect on the appearance of the printed image. Digital printers often use other patterning techniques such as *dithering*, and may have the ability to produce some grayscale on a dot-by-dot

bases. For example, an inkjet printer may create each spot with multiple drops. The more drops used, the darker the color.

There is no simple, linear transformation that maps subtractive devices to tristimulus space. Combining filters multiplies their effect rather than adding them. Most subtractive devices are characterized by measuring a large number of color patches then interpolating between them. Anything that changes the output appearance, such as changing the half-toning algorithm in printing, will change the characterization.

Gamuts and gamut mapping

The gamut of a device creates a volume in the standard space. Only colors that fall within this volume can be reproduced on that particular device. The slides show several gamut representations. The scatterplots represent the gamuts as 3D plots, which is the most accurate way to think about them. Shown are a gamut for an additive system (a monitor), which is a regular shape similar to a cube but with parallelograms for faces. This graphically demonstrates that the transformation from the RGB color cube to CIEXYZ is a linear one. The Cromalin print gamut, however, is distinctly non-linear. While there is some hint of the original cube, each face is a different size and some of the edges are distinctly curved. The gamut is actually concave as well as bent. The gamut for the DLP projector shows a basic additive structure plus an extrusion at the white point caused by selectively adding white. As a result, it is linear in some regions and not in others.

Because the data used to generate the plots was absolute measurement data, the scales are quite different. However, in color management applications, this data would be converted to CIELAB, which normalizes it to a common white (but not necessarily black) value. Another figure in the slides shows gamuts projected onto the CIE chromaticity diagram. Here, linear systems project as triangles whose vertices are the chromaticity coordinates of the red, green and blue primaries. The print gamut, in contrast, is quite irregularly shaped.

To map from one device to another, *gamut mapping* is applied as transformations in this common color space. Current practice is to project colors towards the center of the gamut in a way that reduces saturation, and, to a lesser extent, brightness, while maintaining hue. However, if no in-gamut color is really close, then the reproduction will look substantially different no matter how clever the gamut mapping algorithm. Only redesigning the image can really create a good reproduction.

Color Management Systems

There are a pair of diagrams at the start of this section (courtesy of Michael Bourgojn of Adobe Systems) that succinctly describe the digital color management problem. Given a set of digital input and output devices such as printers, scanners, monitors and film recorders, how do we convert colors between them without creating a customized transform between each pair of devices? The answer is to use a single, device-independent color space, such as those defined by the CIE, as the common interchange format.

Many companies produce color management systems, including Kodak, Agfa, Lineotronic and EFI, just to name a few. Apple's ColorSync is built into the Apple oper-

ating system in such a way that it can import color management engines from a variety of vendors. To support the exchange of profile information across systems, the International Color Consortium (ICC) was formed. This industry consortium has defined a standard profile format that is now commonly used by all commercial systems (www.color.org).

On a Windows machine, the profiles are .icm files. These typically installed with the device driver for a new printer, monitor, etc. These default profiles vary in how well they approximate the actual device, and of course, the system depends on the user to correctly identify the system components. For displays, the contrast and brightness settings must be correct to get a good match. The setup procedures in Photoshop and similar program are designed to help maintain this. Serious practitioners must either invest in profile generation instrumentation and software, or pay to have custom profiles created.

The role of the color management system is to manage the profiles and to transform images from one device to another based on the profile information. Because there is no single “correct” way to make these transformations unless the gamuts match perfectly, different systems will give different results.

Matching image colors based on the CIE color matching metrics is not really sufficient. Image appearance is complex, and while using CIELAB is better than trying to match tristimulus values, it still falls short of being a true image-appearance space. For example, take an image viewed on a monitor that is set with white at a color temperature of D9300 (a very bluish-white that is the default for many computer monitors). Now, reproduce it such that it looks good viewed in normal room lighting (anything from D5000 or warmer). This requires transforming the image white point in a way that mimics chromatic adaptation. The type white point transformation encoded in CIELAB, however, causes unexpected hue shifts. Future systems may include the use of improved color appearance models such as CIECAM 97. These models, however, are more complex to implement than CIELAB, so industry acceptance may be slow.

Color Synthesis

In computer graphics, we are often involved in the synthesis of color. Rendering systems synthesize color from the interaction of lights and surfaces. How the color is specified and represented depends on the rendering model and application. Rendering algorithms are part of graphics systems, where color is represented in a file, rendered, displayed, and integrated with colors and images from other applications. Application designers often provide users tools for selecting individual colors for illustrations, slides, web pages, or other designs. Graphic and information visualization designers have rules and systems for selecting colors, sets of colors and their application.

This section of the talk will discuss all of these areas, which will be presented more as a set of topics rather than as a single, well-integrated story. There are three main sections: Color in rendered graphics, color selection and color design.

Color in Rendered Graphics

Colored lights stimulate the eye directly. However, the light we see when we look at an object is the product of the emission spectrum of the light and the reflectance spectrum of the object. In the Color Playground is a tool that multiplies two spectra to show the sim-

plest form of this effect. In nature, however, interactions between lights and objects is more complex. Shiny surfaces have highlights, rough ones appear textured. Particles and layers as small as the wavelength of light produce shimmering interference effects, like a butterfly wing. Light shining through clouds of small particles produce the blue-gray of smoke, the colors in the sky, and the blue in a child's eyes. It is the goal of rendering research to produce effective models of these processes that can be used to make compelling and beautiful images and animations.

Unlike image reproduction, where the focus is on producing images of objects in the world, computer graphics is focused on producing images of objects that occur only as the result of numerical models. That is, there are virtual objects, and virtual lights that must be rendered to produce a visible image. How they are modeled and rendered defines their appearance. One of the most widely referenced books on color in computer graphics is Roy Hall's *Color and Illumination in Computer Graphics Systems*. Unfortunately, this book is out-of-print. However, most books on rendering include a discussion of color. I have used Andrew Glassner's *Principles of Digital Image Synthesis* as my reference for rendering.

Simulation vs. Design

Philosophically, computer graphics rendering can be organized between two extreme positions that I call simulation and design. The goal of simulation is to model reality. The emphasis is on physically correct representations and rendering algorithms, which for color means at minimum a spectral model of light and surface reflectance. The goal of design, on the other hand, is to produce a visual effect. Most design systems have lots of knobs, and the designer may do unreal things to create the desired result. One of my favorite stories demonstrating this involves an early graphics system that could not produce shadows. Yet the designers were making pictures with shadows in them. How did they do it? They added negative lights. Because the emphasis in design systems is interaction and flexibility, they typically use computationally efficient, RGB-based models.

In simulation systems, the result should be good enough to measure. Rendering involves computing the interaction of light with a material surface. Both the surfaces and the lights should be physically accurate, preferably created by measurement. The equations that control the interaction and scattering of the light should also be physically accurate. Radiosity, and more broadly, global illumination models, are required to describe the interaction of light throughout the scene. To define the visual representation of the image, tristimulus theory at a minimum is used, with more advanced perceptual models a topic of current research.

In design systems, what the final image looks like is the goal. Unreal may be good, as in the negative lights example above. Designers don't object to using physically accurate models, as long as they are efficient and flexible. Because performance is a paramount concern, simple lighting and shading models that can be accelerated with special hardware are the most common in design systems. Most of these have their basis in Phong's original shading model, which is extended to color simply by applying it to RGB independently. Paul Strauss created an extension of this that has become part of SGI's Open Inventor (www.sgi.com), which is a widely-used 3D graphics format. The designer can either simply paint surfaces or vertices with RGB colors, or apply simple material and

lighting models. Color is specified for the surface, its highlight, and its ambient (shadowed) components. Lights, too, are colored based on an RGB specification. RGB or intensity textures can be applied to surfaces. In his original paper, Strauss stated that this model was created to give designers a useful set of parameters for controlling the appearance of their graphics.

Recent SIGGRAPH papers have pushed the design end of the spectrum even further, into *artistic or non-photorealistic rendering*. Gooch shading, presented at SIGGRAPH '98, is a variation of the Phong shading model that mimics the type of shading a professional illustrator would use. It does not represent a realistic lighting model, but is optimized to illustrate the shape of the object being shaded. Several recent papers from the University of Washington have demonstrated rendering techniques that produce images that look like drawings made with traditional media such as pen and ink or watercolor. Amy and Bruce Gooch have now written a book on non-photorealistic rendering that will be published in 2001.

The commercial program *Painter* (was Fractal Design, is now Metagraphics at www.metagraphics.com) is a 2D painting package that does an excellent job of mimicking pens, pencils, paints, and the like. It includes the effect of textured paper as well. While the designers of *Painter* have not published their algorithms, most systems that model ink and paint rely on the Kubulka-Monk model to create their effects. The Kubulka-Monk model describes paint (or any other similar colorant) as a sequence of thin layers. The model describes a way to compute the scattering and absorption in these layers. By varying the thickness of the layers and other parameters, you can get a good model of painted materials.

RGB vs. Spectral Representations

Within rendering systems, the two main ways to represent color are as spectra or as RGB triples. A spectral representation provides the only accurate way to model the interaction of light, direct or reflected, with object colors. An RGB triple can be thought of as a tristimulus representation for the color, or as a view based on color separations. However, while colors can be accurately represented by such triples, their interactions at the spectral level cannot. That is, you can't predict the result of multiplying spectra by multiplying their tristimulus values. Therefore, RGB representations are inherently inaccurate in rendering systems except for the simplest cases. In general, the more spectral computations needed (to model reflections, for example) the less satisfactory the RGB representation.

So why not always use spectral representations? Because they are expensive. The range of wavelengths that comprise the visible spectrum runs from 370-730 nm. Good color measurement instruments sample this at 2 nm intervals, though many sample at 10 or even 20 nm intervals for efficiency. An equally-spaced sampling of the visible spectrum, therefore, contains from 180 to 18 samples that must be stored for every color in the screen and processed for every rendered pixel.

It is possible to generate more efficient representations than uniform sampling if we know something about the possible shapes of the curves we want to represent. The sur-

face reflectances of non-fluorescent objects² are often very smooth, as is the spectral distribution of daylight or of incandescent light. Therefore it is possible to adapt the sampling to give a more efficient representation. Gary Meyer, Roy Hall and Andrew Glassner have all proposed methods for doing this, and Roy Hall has a paper surveying this topic in the July 1999 issue of *IEEE Computer Graphics and Applications*. The most efficient representations use as few as 4 samples/spectrum. Note, however, that a more concise representation may mean a more expensive reconstruction algorithm when the spectra are actually applied in the rendering.

Another way to create an efficient representation for a set of curves is to define basis functions that can be linearly combined. With this approach, only the scalar multipliers for the basis functions need to be stored for each color. Maloney and Wandell have applied this technique to a variety of surface datasets, and Mark Peercy has applied this approach to computer rendering in his SIGGRAPH '93 article.

To display spectra on a monitor, they must be converted to RGB monitor values. Using trichromatic theory and the CIE color matching functions, it is straightforward to convert from spectra to tristimulus values. Because a digital monitor is also a three dimensional additive color system, there is a linear transformation that converts from CIE tristimulus values to the intensity needed for each of R, G and B. This matrix is derived from the tristimulus values that describe the monitor primaries, as is shown in the slides.

RGB representations evolved by simply applying grayscale shading models to the red, green and blue image components independently. The effect is that any color is described as a linear combination of the three display primaries. If all we want to do is specify individual colors, or additive mixtures of them, this is fine. However, in rendering, we multiply the spectrum of the light by the reflectance of the surface. This is not guaranteed to produce another spectrum that can be represented as a linear combination of the display primaries. Said another way, if the RGB values are the tristimulus values for the spectra, the product of the tristimulus values does not equal the tristimulus values of the product of the spectra. The exception is when one of the spectra is an equal energy white, which is often the case for simple graphics systems. A SIGGRAPH '91 paper by Carlos Borges provides an analysis and bound for the error created by using an RGB model.

Using an RGB representation for color can be very effective. Its failings only really appear as the lighting and shading models become more complex. The difficulty of constructing a simple case where RGB fails can be seen using the demonstrations in the Color Playground from Brown University that are included with the CDROM version of these notes.

Viewing Rendered Graphics

All graphics rendering algorithms must ultimately produce an image that can be displayed on a monitor or some other digital display device. The rendering color space is an unbounded, linear intensity space that must be mapped to the bounded, non-linear color space of a display system. As in image reproduction, the issues include definition of the correct RGB primaries, intensity mapping, out-of-gamut colors, and appearance consid-

² Phosphors, which are used in CRT displays or in the coating of fluorescent lights, contain high-energy spikes that must be carefully sampled.

erations.

Rendering systems that use spectral representations are specified absolutely. However, those represented as RGB triples typically are not. For graphics interchange, such as the VRML graphics standard, it is critical to complete the calibration. Otherwise, it is impossible to make the rendering look the same across two different display devices. While many monitors have similar RGB primaries, LCD panels and digital projectors do not. Also, the RGB specification in the rendering space is linear with respect to intensity, whereas most display systems are not. Therefore, both the RGB mapping and the intensity transfer function (ITF) must be determined to create a correct rendering.

Conversions between RGB systems can be accomplished with a 3x3 matrix transformation. For maximum accuracy, this should be performed per pixel. However, as most rendering systems interpolate colors as they fill, providing the transform per vertex would probably be an acceptable approximation. Unfortunately, this is more computation than most graphics systems are designed to apply to this problem.

The intensity mapping can be controlled with 1 or 3 lookup tables. Classic 3D graphics systems are stand-alone applications. They can use the lookup tables in the display controller to control the ITF of the displayed pixels. This is sometimes called “gamma correction” because the goal is to “correct” the non-linear gamma curve of the monitor to be the linear response defined by the rendering system. However, a linear ITF is not perceptually uniform, nor is it an efficient encoding of an 8-bit pixel. Therefore, most desktop systems are not “gamma corrected” to linear intensity. Furthermore, different operating systems set different default ITF’s. As a result, colors on a Macintosh are lighter than those on a PC (actually, it’s a matter of contrast) and darker than on an SGI workstation. There is a slide that summarizes the cross-operating system gamma issues. Charles Poynton has also written extensively on this topic.

In a multi-window, multi-application system, it is appropriate that the linearity of the display be controlled by the operating system because it is a shared resource. Therefore, the issue is not whether the lookup tables in the display controller can be changed by the 3D rendering application, for even if they could, changing them would be a bad idea. Most desktop applications are designed for a non-linear ITF, and would look terrible, or at least very different, linearized. Therefore, the rendering pipeline, not the display hardware, must include the functionality to produce the desired appearance to the viewer.

Classic graphics texts propose displaying the linear intensities produced by the rendering system directly. However, research in the image reproduction domain by Bartleson & Breneman suggest that this will only give the best appearance if the viewing environment matches the original scene. If the viewing environment is darker, the reproduction will need more contrast to look right. They propose specific increases in contrast, expressed as gamma values, to accommodate dim and dark surrounding environments. These are used in the image reproduction industry to improve the appearance of television (dim surround) and projected film (dark surround). Work in web-based graphic standards such as sRGB recommend a non-linear viewing gamma on computer displays, and color appearance models such as CIECAM 97 use the Bartleson & Breneman results to model the effect of the surrounding illumination on color appearance.

Work by Jack Tumblin and Holly Rushmeier apply more complex visual models to de-

termine the ITF for rendered graphics. They describe their results in terms of tone reproduction, and base their results on the Stevens models of brightness. In their results, and in other work by Tumblin, they can more accurately reproduce high-contrast imagery, and create renderings that reflect the absolute brightness of the image. That is, a room lit by a dim light still looks dim compared to one lit by a bright light. Simpler models would normalize both images to the same appearance. Clearly, including perceptual models as part of the rendering pipeline is an important part of making rendered images look more realistic.

Color Selection

One aspect of digital color familiar to almost all users of computer systems is the color selection tool. Color is applied to documents, desktops, drawings and web pages. A typical desktop system might have over a dozen different tools for selecting RGB colors embedded in its applications. I know of no textbooks about designing color selection tools. There are, however, a few ideas that consistently appear. First is the transformation of the RGB color cube into some approximation of a perceptual colorspace. The two most commonly used are the HSV and HLS systems described in the Foley and van Dam graphics texts. Second is the mapping of a 3D space to a 2D, interactive tool. The simplest mapping is sliders for each dimension such as R, G and B. This can be applied to any set of primaries, so graphic arts systems also include C, M, Y and K sliders. Many tools map two dimensions to a plane, then include a linear slider for the third. Many different mappings are possible, and the slides show several examples. Finally, color tools often include palettes of standard colors plus user-defined colors. The standard colors often represent the colors available on a display limited to 16 or 256 colors. There is also usually a pair of patches that show the color being changed and its new value.

One of the original applications of perceptually-based color systems like the Munsell book of color, or the Ostwald system, was for color selection. There have been some efforts to use perceptual spaces as the basis for digital color tools, as well. One of the first that was commercially available was “TekHVC” by Tektronics. The TekHVC space is similar to CIELUV, and the “TekColor Picker” could show slices of the gamuts of two different devices, making it possible to select only in-gamut colors. Giordanno Beretta’s “MetaPalette” used the CIELAB space to select palettes of harmonious colors. His work influenced the “Canon Color Advisor,” a clever tool buried in the print driver of Canon color printers.

Another form of color selection is to use color names. There is something fundamental about naming color. Ask someone to describe a color and they will begin first with a hue name such as blue or green. Berlin and Kay discovered that color names are common to human language, and that there are a standard set of 11 simple color names that appear in all mature languages. These are the perceptual primaries (red, green, blue, yellow, black, white and gray) plus orange, purple, pink and brown. Furthermore, the order the names are introduced into the language is consistent across languages. Boynton and Olson have further studied the psychophysics of color names with a set of color naming experiments. They found that there was a high degree of correlation between the names given colors across people and cultures. That is, the color patches described as “red” by one person will also be described as red by another. Of course, not all colors have simple names, and

there is less agreement on these. But for the agreement for the basic colors was very good. A recent PhD thesis by Johan Lammens, which is available on-line, is an excellent reference for the perceptual basis for color names.

Color names are also important for industrial applications. In 1976, the National Bureau of Standards published *A Universal Color Language and Dictionary of Names*, by Kelly and Judd. This describes both an orderly language for specifying color, calibrated to the Munsell color space, and a mapping into this language of thousands of industrial color names. For example, the color “avocado” could be described as “dark olive green.” Berk, Brownston, and Kaufman published an article in 1982 that introduced a simplified, more computationally tractable version of the NBS Color Language. We had an implementation of their system (plus our own improvements) running at Xerox PARC in the 80’s. I found an advertisement for a commercial implementation of the NBS Color Language as part of the Color Science Library, from the CGSD Corporation in Palo Alto, CA (www.cgsd.com). It looks like a useful package, but I haven’t tried it myself.

In the graphics arts domain, the Pantone Matching System® (www.pantone.com) is a common way of describing colors. Originally published as a book of print samples, the digital form of this system is incorporated in most of the major graphic arts applications such as Adobe Illustrator or Quark Express.

Finally, dictionaries of color names are starting to be used for specifying colors in HTML, X-Windows and probably other applications. The names I have seen are simply a binding of a text string to an RGB triple. I have some reservations about the names themselves (what color is “silver” anyway, on a computer monitor?) But, the idea of naming is a good one. Names tend to limit the set of colors specified, and this can be good, which is why specifying hundreds of names is bad. In the X-window implementation, the name dictionary provides a useful level of indirection in the color specification. Say you design a tool that includes “brown” text on a “tan” background. You then discover that text becomes illegible with that combination of colors on a 256 color display. You can simply change the specification of the names once, and have the effect appear everywhere.

Color Design

I am not a formally trained graphic designer or illustrator, though I’m a pretty experienced amateur, as are many of us in the graphics field. For the discussion on visual design, I rely on a book by Wucius Wong called *Principles of Color Design*. Personally, I find Wong’s systematic approach to design very clear and compelling. On the other hand, if you go to the graphic arts section of your local bookstore and look for a book on color design, most of what you will find is books of color schemes represented as color palettes. Whelan’s, *Color Harmony 2* came with a palette selection tool (the PalettePicker) on CDROM, so I chose it as my example of such an approach. Edward Tufte is famous for his books on information visualization, and *Envisioning Information* contains a chapter on the use of color. I will conclude with a brief summary of his view on how and why to use color for visualization.

Color Harmony

The color circle used by designers is quite similar to the circle of hues described in a per-

ceptually based color system such as Munsell. The circle is formed starting with three primaries, red, yellow and blue, plus three secondaries created by mixing the primaries pairwise: orange, green and purple. The full circle contains all the pairwise mixtures of these six colors as well. I am often asked why the primaries are not cyan, magenta and yellow. The answer may be more a one of naming than of function. The printing ink magenta is a slightly purplish red, and the cyan is more or a true blue than its overprint with magenta, which is a purplish, almost navy blue. To one not familiar with printing terminology, they could naturally be called blue, red and yellow.

The other reason may be simply one of history and application. The cyan, magenta and yellow primaries used in an image reproduction system are carefully chosen to create the largest possible gamut. They are subject to strong constraints as to function and cost. The designer's colorspace was traditionally formed by mixing paints. There is more flexibility in the exact choice of colors, which can be adjusted for an individual design. Whether layered or blended, the mixing principles are similar for both sets of subtractive primaries.

The other dimensions of a designer's colorspace are lightness and saturation. Again, these are similar to the perceptual spaces discussed earlier. In fact, Wong uses the Munsell space and terminology (hue, value and chroma) to describe color design. Knowing that Munsell was an artist as well as a color scientist, makes this less surprising.

The term *tint* applies to a color that has been lightened and desaturated by mixing it with white. A *tone* is a color grayed and darkened by mixing it with black. The *complement* of a color lies opposite it in the color wheel. A color mixed with its complement will become neutral, or gray.

The concept of *color harmony* is defined by Wong as "successful color combinations, whether these please the eye by using analogous colors, or excite the eye with contrasts." Analogous colors are similar, contrasting colors are opposites. He then goes on to demonstrate these principles applied to the hue, value and chroma of colors, using many beautiful examples.

Color palettes are sets of 2-3 colors, plus their tints and tones, that are used in a design. They are often described in terms of qualities ranging from semi-scientific (contrast, neutral, primary) to emotional (warm, elegant, exciting). An important issue when designing a palette is the message you are trying to convey with your choice of color. Now, using palettes in design is an excellent idea. It provides an overall visual coherence that is very important. And, people's emotional response to color is very real. So whether or not you are comfortable with labels like "elegant," having access to predesigned palettes, or better yet, the ability to custom design effective color palettes, should help improve the appearance of our graphics. It is interesting, however, that all the color tools described in the previous section really only support selecting one color at a time. Even those that provide "palettes" do not provide any way to name, manage or reuse those palettes. Professional graphic design systems such as Adobe Illustrator seem to do a somewhat better job in this area, but I suspect there is far more that could be done to support palettes and other design principles in our digital tools.

Effective use of color

The goal in selecting colors is, ultimately, to produce an image that is both attractive and that conveys its message effectively. It is difficult to describe the “effective” use of color unconstrained by any application. However, there are a few common principles worth mentioning here.

Color is very eye-catching, creating emphasis, clustering, and evoking relationships to the known world. According to Tufte, the primary rule for the use of color “do no harm.” Color should be clarifying, not confusing. It should be tasteful, and it should be robust across media, viewing conditions and viewers.

Color can be used to identify or label objects in an illustration. A classic example is shown in the slides. Take a page of numbers and count all the 7’s. Studies have shown that the amount of time to count them is proportional to the number of digits on the page. That is, to count the 7’s you must look at each digit in turn to determine whether or not it is a 7. Now, color the 7’s some distinctive color such as red. Now the time it takes to count the 7’s is proportional to the number of 7’s on the page. The red color labels the 7’s so all you have to do is count them up. Color works extremely well as this type of label as long as the identifying color is distinct within its context. Colored roadways or icons on maps, or colored text to identify hyperlinks are examples of color labels.

Color scales can be used to indicate quantity. There are no real intuitive hue orderings except possibly one for temperature (blue to red), but lightness or saturation scales are often effective for defining relative values. Colors distributed on a plane also create visual clusters of similar values. Examples are thermometer scales or density plots.

The world we see around us is colored, and colors in illustration often reflect their use in the physical domain. For example, stop signs and lights are red, so stop “buttons” are also. Geographic maps tint water blue and earth brown. The icons shown on the slide mimic the color of the fruits they represent, although the colors themselves do not match the natural object well. This is often true of color in illustrations.

Finally, we use color because it is beautiful. Most people spend some amount of effort to make the colors in their environment match their aesthetic taste. Look at the way people decorate their workspaces, or color their computer desktops. Color impacts emotions, which can impact performance. While the value of aesthetics is often questioned in “practical” disciplines like science and engineering, it impacts even these fields. An attractive illustration will be more appealing to look at and will therefore be more effective.

Adding color to illustrations and information visualization system in a way that is robust across systems, media and viewers can be very hard. Without color management, a carefully designed presentation on one medium can become a muddled mess on another. For example, I had a colleague who used bright green text on a dark green background for slides. On the monitor, the text was quite legible and the overall appearance was pleasing. Transferred to slides using a film recorder, however, the result was overall very dark and lacked the contrast needed to comfortably read the text. Even an excellent color management system would not have completely saved him, as his text color was far outside of the film gamut.

A primary issue for effectiveness is legibility, especially for text. The key to legibility is

brightness contrast, which is why black text on white paper (or white text on dark slides) is so popular. In fact, an edge defined by only hue difference cannot be seen. Such an example is difficult to construct, but I can assure you, it is very disconcerting. You can see that two adjacent regions are differently colored, but it is impossible to find the edge between them. Another issue for text legibility is the distribution and focus of the short wavelength or blue cones as compared to the red and green cones. The blue cones are much more sparse, and focus on a slightly different plane than the other two. This is why some colors of bright blue text appear blurry—they are stimulating primarily the blue cones, which do not provide the same acuity as the others. The slides show a diagram from Mark Fairchild that shows the relative distribution of the three cone types. Note that there are no blue cones in the very center of the retina.

Another type of cross media problem has to do with grayscale and color-mapped displays. Grayscale systems, of course, must map all colors to gray values. Care must be taken that these grays will function as replacements for the colors. Many desktop systems display a maximum of 256 colors, using dithering to approximate the rest. Dithered text and other fine features are often illegible, so it is important to choose colors that will remain solid. This is also true for printers, especially for low-resolution digital desktop systems. Text and fine features are much more crisp when they contain at least one solid separation, even in offset printing. A rather nice feature of the Netscape web browsers is that they automatically map text to solid colors on dithered displays. I wish more applications did this.

All viewers are not the same either. As noted in the vision section, a significant part of the population has atypical color vision. As the red-green anomalies are the most common, one rule of thumb is to avoid encoding purely with a red-green distinction (an issue that apparently never occurred to the designers of stoplights). However, to ensure that important information can be distinguished by everyone, color should be combined with shape or other ways of encoding the information (like a stop sign). Another viewer issue is poor acuity, or lack of focus. Not all acuity problems can be fully corrected with lenses. Also, the eye gradually loses its ability to change focus as people age, which is why most people need some form of “reading glasses” by the time they are fifty. Avoiding small, low-contrast text and other features is important to accommodate this problem. Pill-bottle labels with small colored letters on a colored background should be banned!

In summary, when in doubt, use color conservatively. Duplicate the information carried by the color whenever possible. Know your target media and audience well, and be sure to test your designs thoroughly.

Annotated Bibliography

I have organized this bibliography by section, though there will naturally be some references that span sections.

Introduction

A good general book on color is Williamson and Cummins *Light and Color In Nature and Art*. It was designed for an undergraduate course and includes information on physics and optics as relates to color, as well as many of the topics covered in this tutorial.

1. S. J. Williamson and H. Z. Cummins. *Light and Color In Nature and Art*. John Wiley & Sons (1983).

Color Vision

There are many excellent color vision textbooks. I chose Wandell's because it is recent and has a computational flavor that should appeal to the technical members of the graphics audience. I also mentioned the text by Leo Hurvich, which is out-of-print but should be available in academic libraries. There are a couple of other vision texts worth mentioning, though I am personally only familiar with one of them. Cornsweet's 1970 book is a classic, though now 30 years old. David Marr's book provides a less conventional yet intriguing model for vision.

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. A substantial amount of this book is tables of numbers, which nowadays would be presented on CDROM. Interestingly enough, this book has no color pictures. Another classic book on color science and its application is Judd and Wyszecki's *Color in Business, Science, and Industry*.

Mark Fairchild's book is the best reference on color appearance models. Josef Albers book, *Interaction of Color*, is famous for its color illustrations. It comes in two forms, an expensive hardback (\$135) with a full set of color plates, or a somewhat abridged paperback version for approximately \$10. I have the paperback, and have found it quite useful.

2. Brian Wandell. *Foundations of Vision*. Sinauer Associates Inc. (1995).
3. Leo M. Hurvich. *Color Vision*. Sinauer Associates Inc. (1980).
4. Tom Cornsweet. *Visual Perception*. Academic Press (1970).
5. David Marr. *Vision*. W. H. Freeman, San Francisco, CA. (1982).
6. Judd, D. B. and G. Wyszecki. *Color in Business, Science, and Industry*. John Wiley & Sons (1975).
7. G. Wyszecki and W.S. Stiles. *Color Science, Second Edition*. John Wiley & Sons (1982).
8. Mark D. Fairchild. *Color Appearance Models*. Addison-Wesley (1998).
9. Josef Albers. *Interaction of Color*. Yale University Press (1963).

Color Reproduction and Management

Robert Hunt's *The Reproduction of Colour* is an invaluable reference for color reproduction technology. Now in its 5th edition, it is a must-have for anyone interested in this aspect of color. Gary Field has two newer books on the topic, *Color and Its Reproduction, 2nd Edition* and *Principles of Color Reproduction*, an update of John Yule's classic book on printing, which has long been out of print. 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. In spite of the full-color production, it is reasonably priced at around \$70. Charles Poynton, who regularly teaches about digital color at SIGGRAPH, has written a complete reference on digital video. His courses often include a section on color reproduction and color management. There is active research in the area of digital color reproduction systems and color management. Much of this work is published at conferences and in publications supported by the *Society for Imaging Science and Technology*, or IS&T (www.imaging.org). Their "Recent Progress" Series are bound volumes of select papers on topics such as color management and color science. The Graphic Arts Technical Foundation (www.gatf.org) is also a good source of practical information on color and printing. Its publications can be ordered online through the Graphic Arts Information Network (www.gain.org). The Society of Information Display (www.sid.org) is a good source of references on display technologies. I've found *Display Systems* and *Projection Displays*, from the Wiley SID Series in Display Technology particularly useful.

10. R.W.G. Hunt. *The Reproduction of Colour, Fifth Edition*. Fountain Press, England (1996).
11. G. G. Field, *Color and Its Reproduction, 2nd Edition*, GATF Press, 1999.
12. J. A. C. Yule with G. G. Field, *Principles of Color Reproduction: Applied to photomechanical reproduction, color photography, and the ink, paper, and other related industries*, GATF Press, 2001.
13. E.J. Giorgianni and T. E. Madden. *Digital Color Management*. Addison-Wesley (1998).
14. C. A. Poynton. *A Technical Introduction to Digital Video*. John Wiley & Sons (1996).
15. L.W. MacDonald and A.C. Lowe, *Display Systems*, John Wiley and Sons (1997).
16. E.H. Stupp and M. S. Brennesholtz, *Projection Displays*, John Wiley and Sons (1999).

Color Synthesis

The primary reference I used for the rendering section of this tutorial is Andrew Glassner's big, two-volume work, *Principles of Digital Image Synthesis*. I am not a rendering expert, so I relied heavily on Andrew's presentation. Andrew's references are encyclopedic, but I duplicate a few here for convenience. Roy Hall's book is out of print and not as recent, so I did not use it as much. Roy does have, however, a recent paper on the topic of spectral representations for rendering in the July 1999 issue of CG&A. Murphy and Doherty's beautiful book on the forms of color in nature can be ordered through the Exploratorium website (www.exploratorium.com). The McCamy reference is for the

Macbeth ColorChecker used in the linear models example, which can be found at many photography stores or through GretagMacbeth (www.gretagmacbeth.com)

17. Andrew Glassner. *Principles of Digital Image Synthesis*. Morgan Kaufmann, San Francisco, CA (1995).
18. Gary Meyer. "Wavelength Selection for Synthetic Image Generation," *Computer Vision, Graphics, and Image Processing*, vol. 41, pp. 57-79. (1988).
19. Mark Peercy. "Linear color representations for full spectral rendering," *Computer Graphics*, 27, 3, 191-198, August 1993.
20. Carlos Borges, "Trichromatic Approximation for Computer Graphics Illumination Models," *Computer Graphics*, 25,4, July 1991, pp. 101-104 (1991).
21. Paul Strauss, "A realistic lighting model for computer animators." *IEEE Computer Graphics & Applications*, 10(11):56-64, November (1990).
22. Roy Hall. *Illumination and Color in Computer Generated Imagery*. Springer-Verlag, NY, NY. 1989.
23. Roy Hall. "A Comparison between XYZ, RGB, and Sampled Spectral Color Computation." *IEEE Computer Graphics and Applications*, July, 1999.
24. P. Murphy and P. Doherty, *The Color of Nature*, Exploratorium Books (1996).
25. C. S. McCamy, H. Marcus, and J. G. Davidson. "A color-rendition chart." *Journal of Applied Photographic Engineering*, 2(3):95-99, summer (1976).

Artistic, or non-photorealistic rendering has been the topic of many recent SIGGRAPH papers from David Salesin's group at the University of Washington. Winkenbach's work on applying Salisbury's pen and ink textures to rendering is one of the first in this series applied directly to 3D rendering. Curtis extends the model to watercolor. The original Kubelka-Monk reference is difficult to find, but Glassner includes a good explanation in his book. Gooch shading, presented at SIGGRAPH 98, extends the Phong model to techniques for technical illustration. The Gooches have written a book on the topic, which should be available by SIGGRAPH 2001.

26. M. P. Salisbury, S. E. Anderson, R. Barzel and D. H. Salesin. "Interactive Pen-and-Ink Illustration," Proceedings of SIGGRAPH 94, (Orlando, FL July 24-29, 1994), in *Computer Graphics Proceedings*, ACM SIGGRAPH, pp. 101-118 (1994).
27. G. Winkenbach and D. H. Salesin. "Computer Generated Pen-and-Ink Illustration," Proceedings of SIGGRAPH 94, (Orlando, FL, July 24-29, 1994), in *Computer Graphics Proceedings*, ACM SIGGRAPH, pp. 91-100 (1994).
28. C. Curtis, S. E. Anderson, K. W. Fleischer, D. H. Salesin. "Computer-Generated Watercolor," Proceedings of SIGGRAPH 97, (Los Angeles, CA, August 3-8, 1997), in *Computer Graphics Proceedings*, ACM SIGGRAPH, pp. 421-430 (1997).
29. A. Gooch, B. Gooch, P. Shirley, E. Cohen. "A Non-Photorealistic Lighting Model for Automatic Technical Illustration," Proceedings of SIGGRAPH 98, (Orlando, FL, July 19-24, 1998), in *Computer Graphics Proceedings*, ACM SIGGRAPH, pp. 447-452 (1998).

30. A. Gooch, B. Gooch, *Non-photorealistic rendering*, A.K. Peters, Natick, MA, (2001).

I first explored color issues with the exchange and rendering of 3D graphic for the web and desktop environments working with the VRML standard (www.web3d.org). A paper at the 1997 Color Imaging Conference describes it as a “work in progress.” Charles Poynton has written extensively about gamma, both formally and on his website (<http://www.inforamp.net/~poynton/>). The sRGB colorspace and recommended practices have been adopted by the International Electrotechnical Commission (IEC) as IEC 61966-2-1 (<http://www.iec.ch/home-e.htm>).

31. Maureen Stone. “Color in Web-based 3D Graphics,” Proceedings of the IS&T/SID Color Imaging Conference, Scottsdale, AZ, November (1997).
32. Charles Poynton. The Rehabilitation of Gamma,” Proceedings of SPIE 3299 (San Jose, Calif., Jan. 26-30, 1998), 232-249 (Bellingham, Wash.: SPIE, 1998).

Tumblin and Rushmeier’s original paper is available both as an IEEE CG&A journal article and as a tech report from Georgia Tech. Tumblin has done further work in this area, some of which is reflected in the TOG article listed, his SIGGRAPH 2000 paper, and in his PhD thesis. Mark Fairchild, together with the Cornell computer graphics group, have been working to develop a framework for appearance and rendering, as was reported in a SIGGRAPH ‘98 paper.

33. J. Tumblin & H. Rushmeier, “Tone Reproduction for Realistic Images” *IEEE Computer Graphics & Applications*, Vol. 14, No. 6, pp.42-48. Nov. 1993. Extended versions as Ga. Tech GVU Center Technical Report GIT-GVU-91-13, and 92-32.
34. J. Tumblin, J. Hodgins, & B. Guenter. “Two Methods for Display of High Contrast Images” *ACM Transactions on Graphics*, **18**, 1, January 1999.
35. S. N. Pattanaik, J. Tumblin, H. Yee, D. P. Greenberg, “Time-Dependent Visual Adaptation for Realistic Image Display,” Proceedings of SIGGRAPH 2000, (New Orleans, LA, July 23-28, 2000), in *Computer Graphics Proceedings*, ACM SIGGRAPH, pp. 47-54 (2000).
36. S.N. Pattanaik, J. A. Ferwerda, M.D. Fairchild, D.P. Greenberg. “A Multiscale Model for Adaptation and Spatial Vision for Realistic Image Display.” Proceedings of SIGGRAPH 98, (Orlando, FL, July 19-24, 1998), in *Computer Graphics Proceedings*, ACM SIGGRAPH, pp. 287-298 (1998).

I know of no scholarly references on designing color selection tools, so I relied on my own observations, which I hope are not too idiosyncratic. The HSV colorspace was invented by Alvy Ray Smith and presented in a 1978 SIGGRAPH paper. The following year the HLS space was recommended by the Computer Graphics Standards Planning Committee. These spaces are also described in the Foley and van Dam textbooks. Similar transformations of the RGB color cube have probably been created by many practitioners. The TekHVC space and the TekColor Picker were developed by Tektronics in the late 1980’s, as was the work at Xerox on MetaPalette. The MetaPalette evolved into the

Canon Color Advisor, which was described in at a recent IS&T Color Imaging Conference.

37. Alvy Ray Smith “Color gamut transform pairs,” *Computer Graphics*, 12(3):12-25. (1978).
38. “Status Report of the Graphics Standards Planning Committee,” *Computer Graphics* 13(3), August (1979).
39. J. Foley, A. van Dam, S. Feiner and J. Hughes. *Computer Graphics Principles and Practices*. Addison-Wesley (1990).
40. 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).
41. 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).
42. 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).

Color naming has been well studied. The most complete reference in the psychophysical domain is Lammen’s thesis. It contains many other references in its bibliography. I include the reference to Boynton and Olson’s work here also. Berlin and Kay’s anthropological work on color naming was originally published in 1969, and was reprinted in 1990. The National Bureau of Standards has become NIST, the National Institute of Standards and Technology (www.nist.gov). The Pantone color matching products can be ordered from Pantone (www.pantone.com).

43. 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).
44. Robert Boynton and Conrad Olson. “Locating basic colors in the OSA space,” *Color Research and Application*, 12(2):94-105. 1987.
45. Brent Berlin and Paul Kay. *Basic Color Terms: Their Universality and Evolution*, University of California Press, Berkeley CA, 1991 edition., originally published in 1969.
46. 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).
47. T. Berk, L. Brownston, and A. Kaufman. “A new color-naming system for graphics languages.” *IEEE Computer Graphics and Applications*. 2, 3 (1982).

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. Whelen’s *Color Harmony* contains a full set of palettes plus a Windows application called the “Palette Picker” that is also available from www.lightdream.com. The Palette Picker lets you select palettes in three ways: by “scientific” name, by “aesthetic” name, or to harmonize with a selected color. The tool is not bad—it comes up with plausible palettes. It can only display their RGB or CMYK encoding, however, which then have to be copied by hand into another application. Tufte

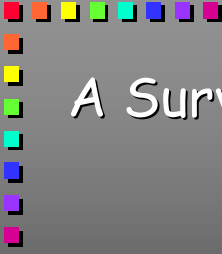
is famous for his books on information visualization. The only one of his three books that contains a chapter about color is *Envisioning Information*.

48. Wucius Wong. *Principles of Color Design, second edition*. John Wiley & Sons, NY, 1997.
49. Bride M. Whelan, *Color Harmony 2*. Rockport Publishers, Rockport, Mass., 1997.
50. Edward R. Tufte, *Envisioning Information*. Graphics Press, 1990.

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.

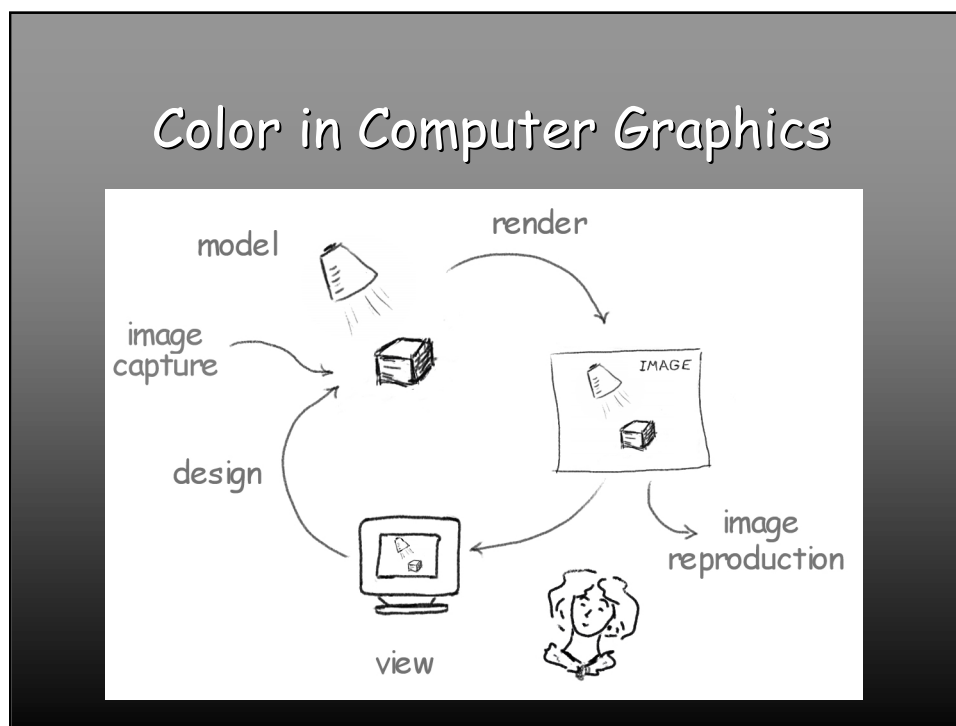
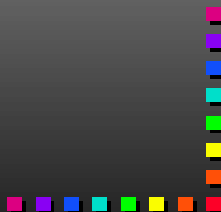
In the printed version of these notes, color plates will appear at the end of the slides that contain selected images and illustrations that only work when seen in color.

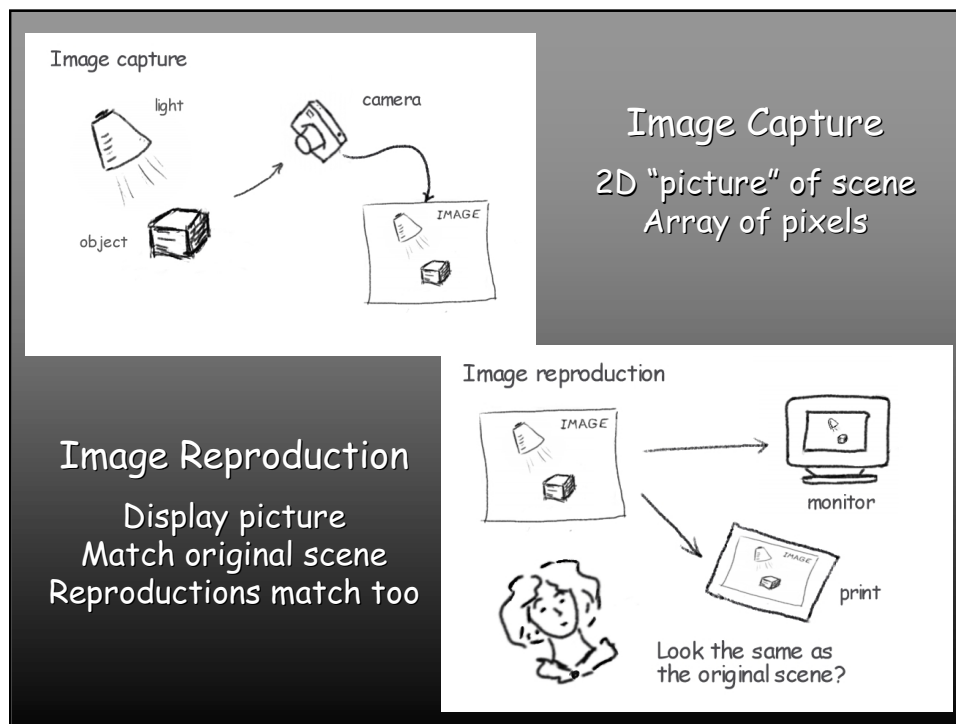
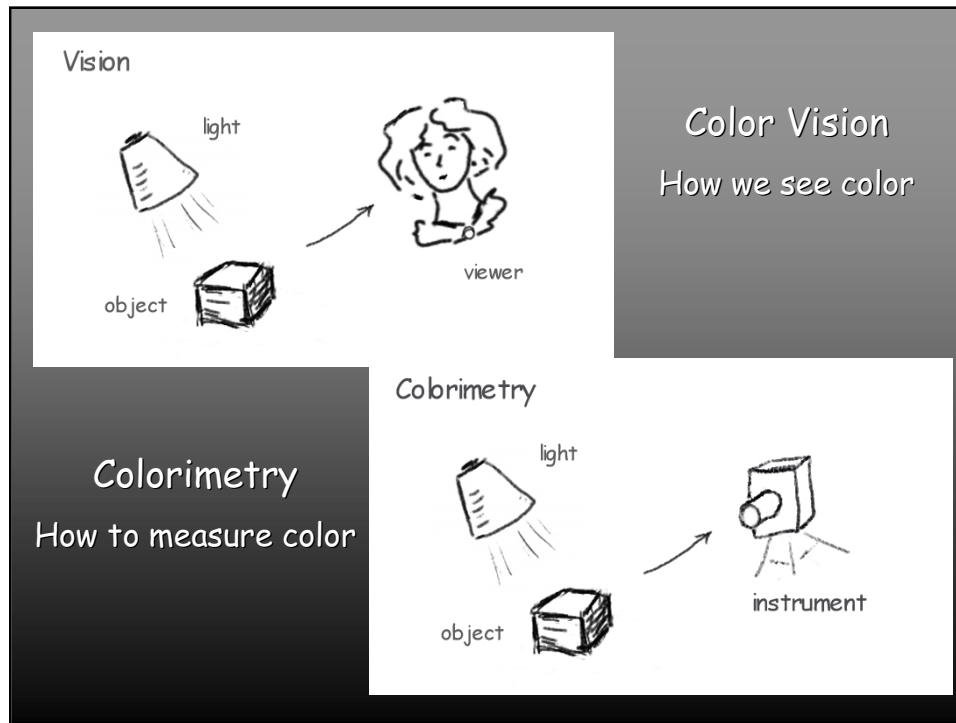


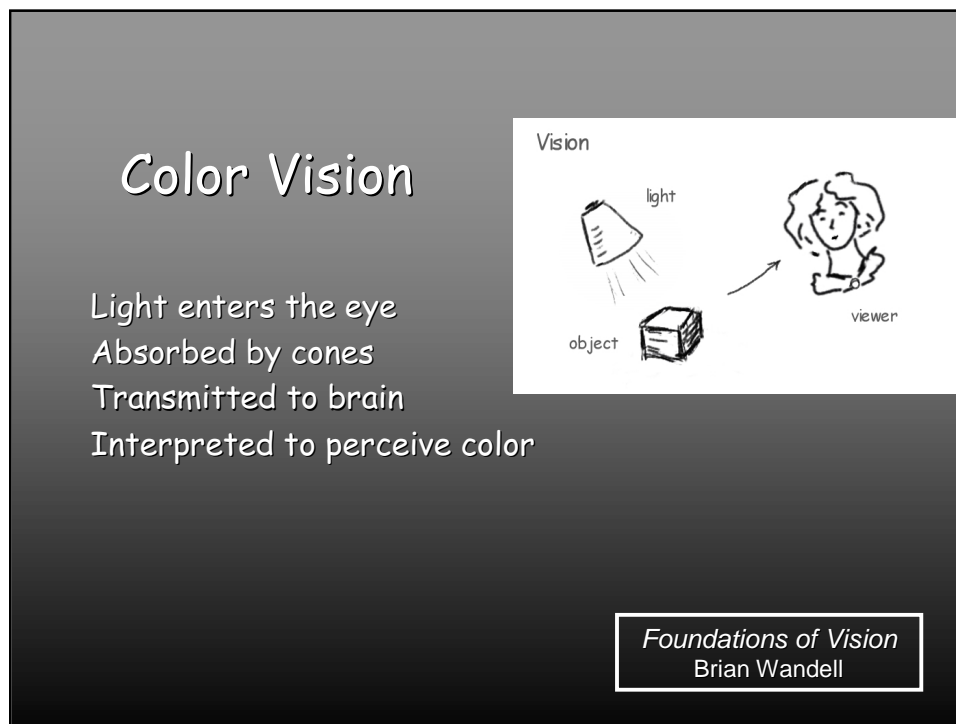
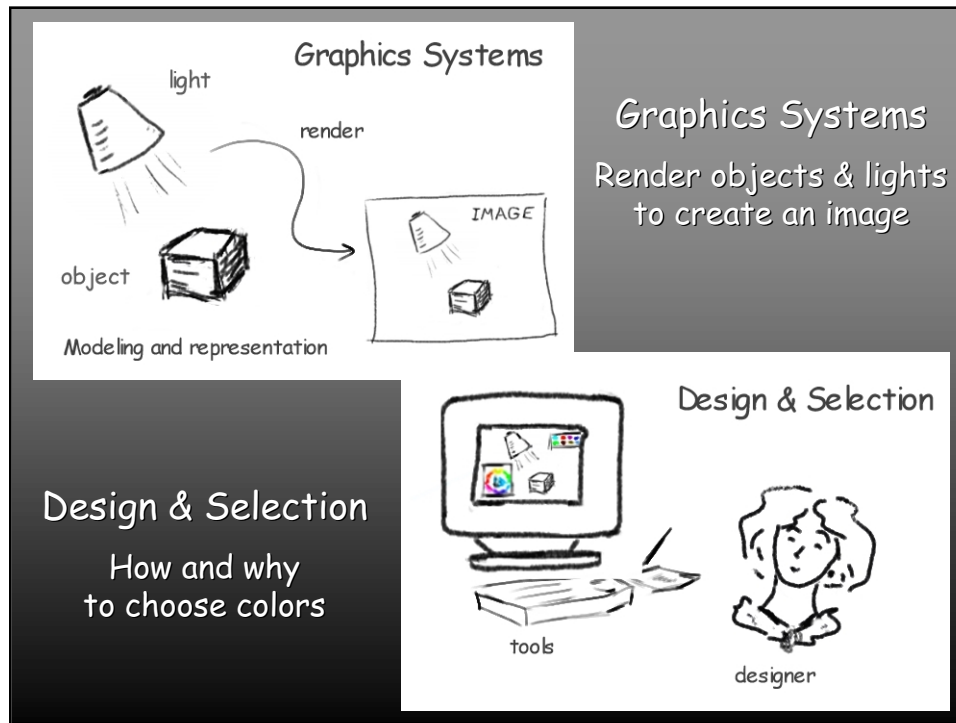
A Survey of Color for Computer Graphics

Maureen Stone
StoneSoup Consulting

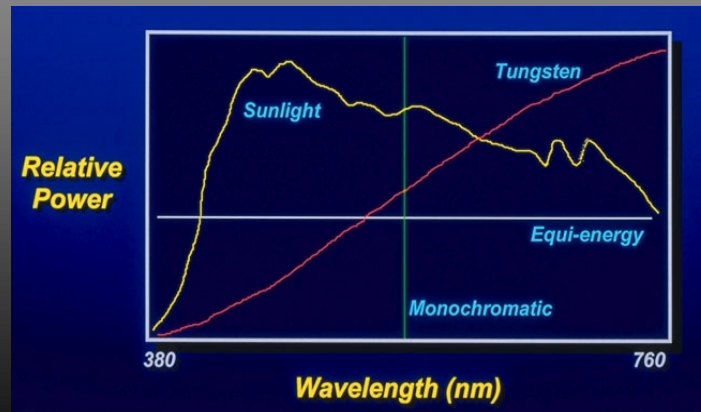
SIGGRAPH 2001, Course 4







Spectral Distribution Various Light Sources



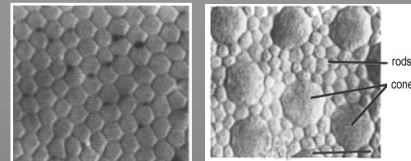
Cones and Rods

Cones: color vision

- Photopic vision
- Daylight levels
- Concentrated in fovea (center)

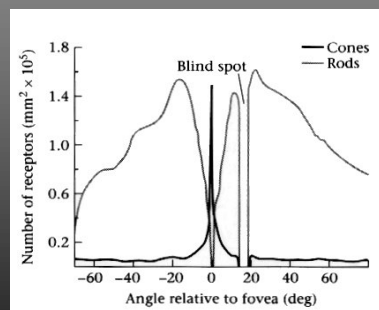
Rods: grayscale

- Low light levels
- Scotopic vision
- Peripheral vision



Fovial cones

Cones and rods



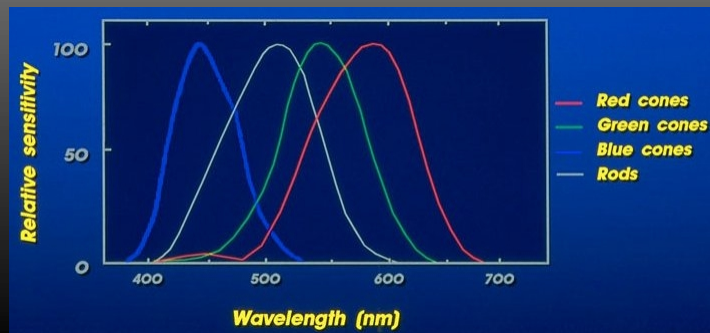
Distribution of rods and cones

From Foundations of Vision, fig 3.1 & 3.4,
© Brian Wandell, Stanford University

Cone Response Curves

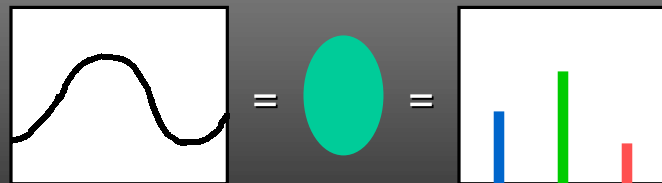
Cone response is a function of wavelength
 For a given spectrum

- Multiply by response curve
- Integrate to get response



Metamerism

Brain sees only cone response
 Different spectra appear the same



Fundamental principle of
 color reproduction

ColorWeb Demo

Java applets demonstrating color concepts

Brown University Graphics Group

- John Hughes, Anne Spalter
- Adam Dopplet, Jeff Beall, Robert George

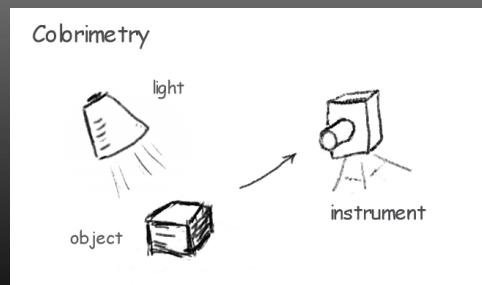
Electronic Schoolhouse Playground



Colorimetry

Measurement of color

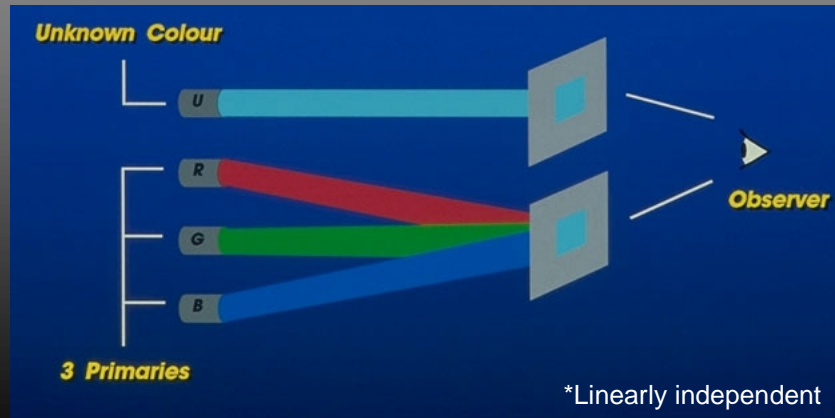
- Instruments that work like the eye
- Industrial and scientific application



Color Science
Wyszecki & Stiles

Color Matching Experiments

Match any color by adding any* three primaries



Tristimulus Values

Power of the primaries

- Define color by three numbers
- Specific to a set of primaries

Some restrictions apply

- Single colors
- Common viewing conditions
- Response, not appearance

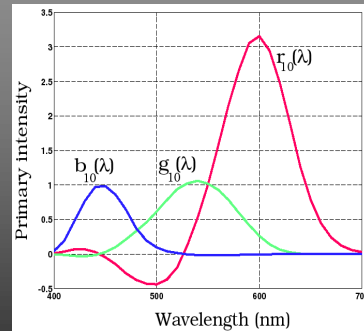
Color Matching Functions

To match any spectrum

- Multiply by CMF
- Integrate to get the tristimulus values

To create a set of CMF's

- Pick three primaries
- Match monochromatic colors
- Plot values vs. wavelength



R=645 nm, G=526 nm, B=444 nm
Styles & Burch

CIE Standard

Commission Internationale de l'Eclairage

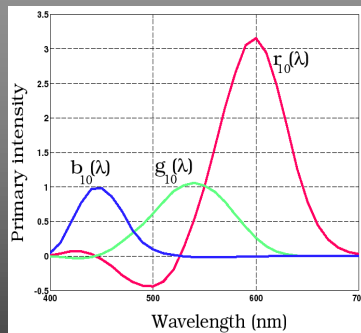
Formalized color matching

- Standard primaries
- Standard observer

Standard representation

- Linear transform
- CMF's all positive
- Easy to compute

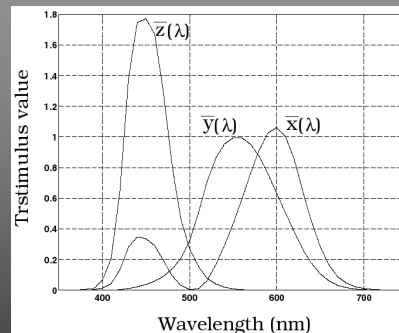
Stiles and Burch



Measured basis

- Monochromatic lights
- Physical observations
- Negative lobes

CIE Standard



Transformed basis

- "Imaginary" lights
- All positive, unit area
- $\bar{y}(\lambda)$ is luminance

CIE Standard Notation

Color matching functions

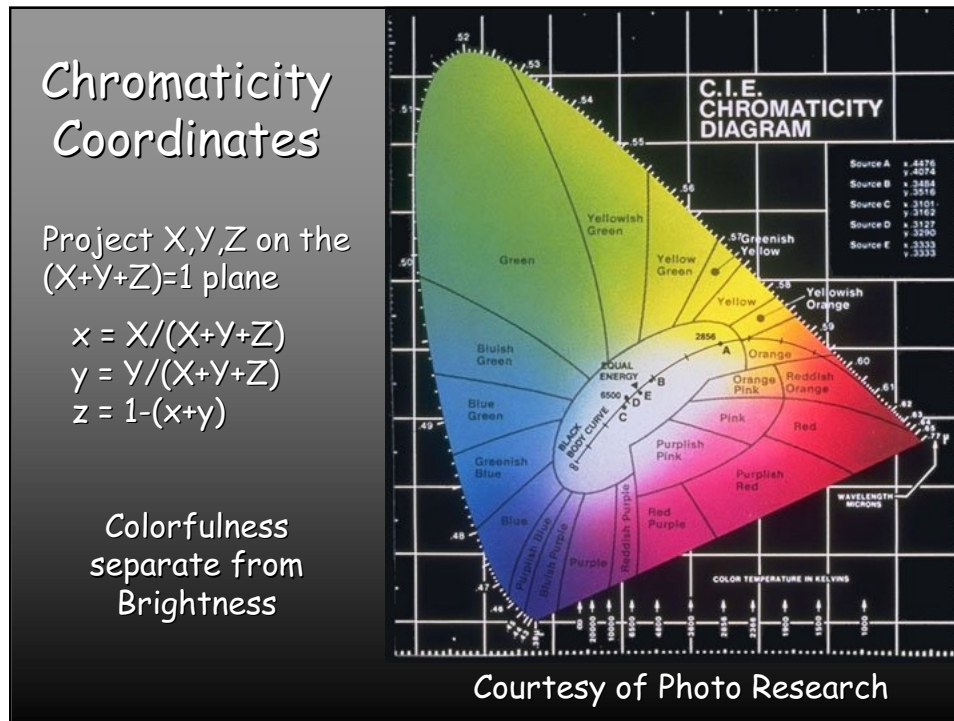
- $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$
- Apply to measured spectrum

CIE tristimulus values

- X, Y, Z
- Power of the CMF's

CIE chromaticity coordinates

- x, y or u, v
- Standard 2D diagram



Color as a Linear System

Grassman's additivity law

- Spectrum: $s = a + b$
- Response: $RGB_s = RGB_a + RGB_b$

Linear basis

- Color matching primaries
- 3x3 matrix conversions

Applies to tristimulus values and CMF's

Summary

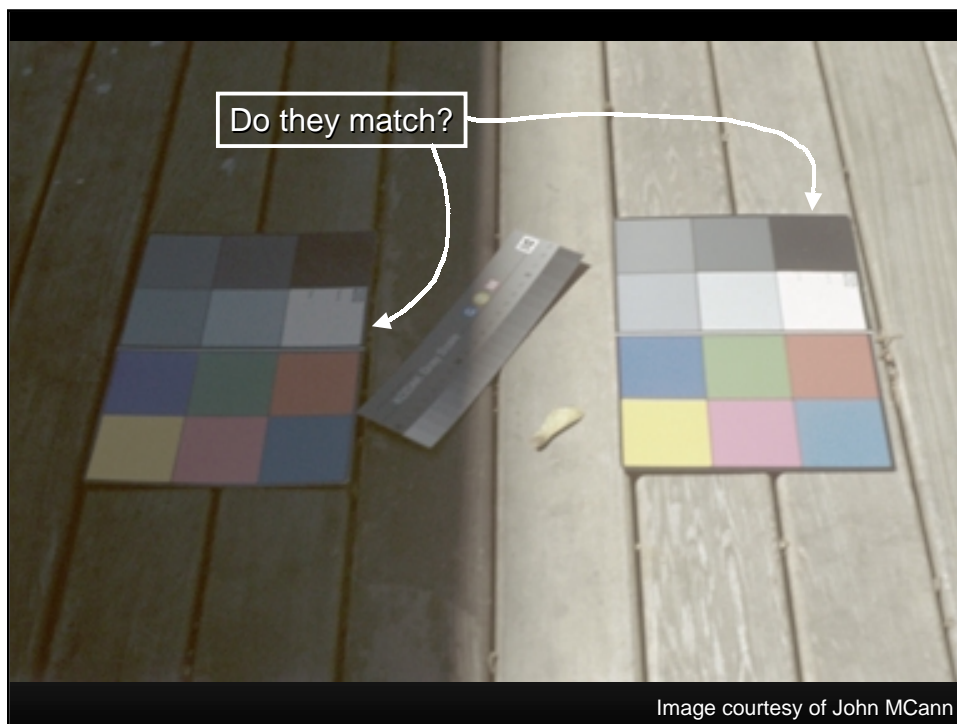
First level visual processing

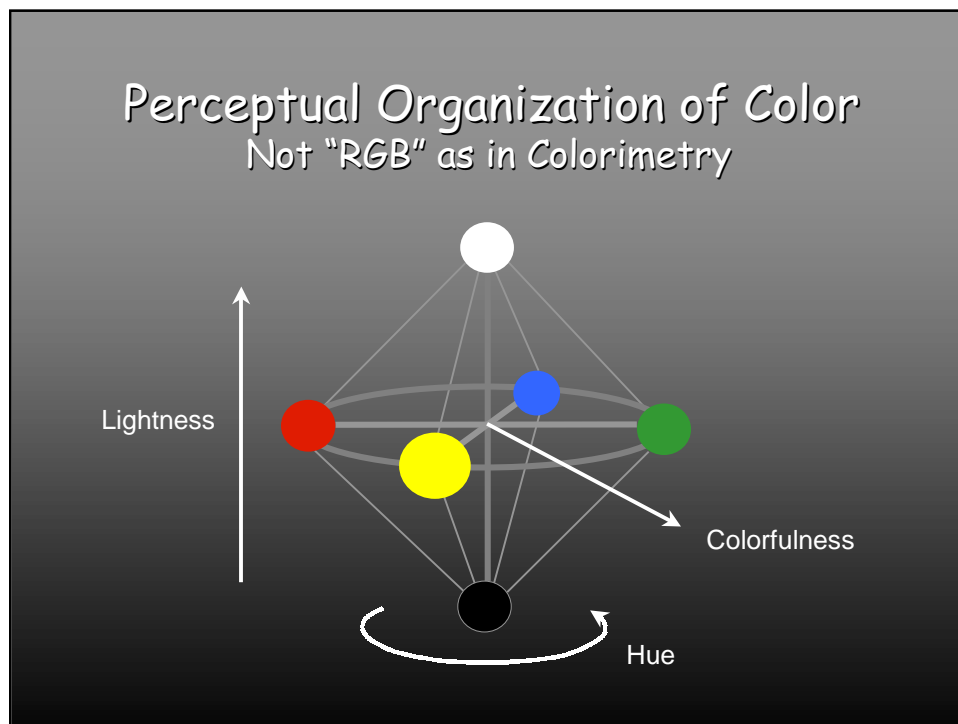
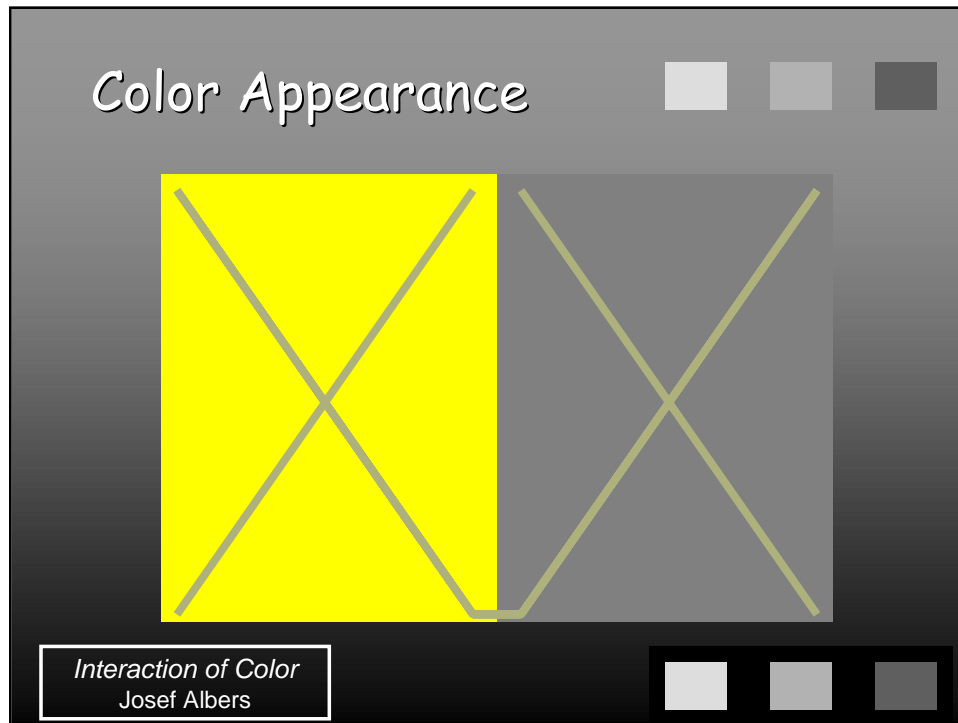
- Trichromacy—Three cones respond to spectrum
- Metamerism—response, not spectrum

Colorimetry

- Color measurement
- Color matching functions & tristimulus values

But does what it LOOK like?



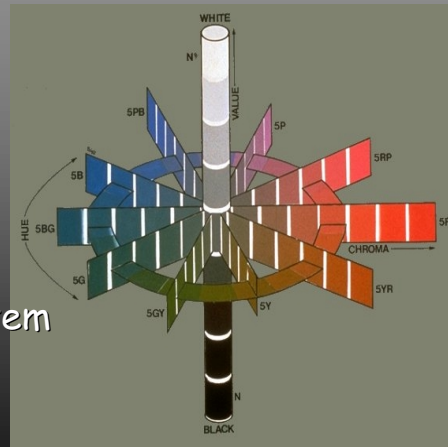


Munsell Color Space

Chroma, Hue, Value

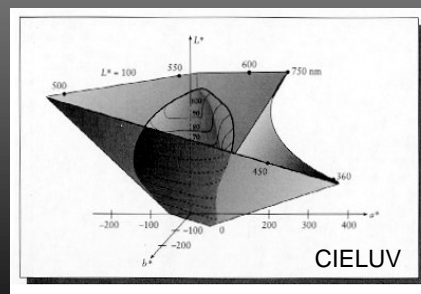
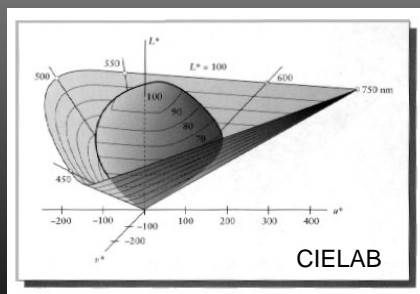
- 5 R 5/10 (bright red)
- Unique black & white
- Perceptually uniform
- Book of painted chips

Munsell Renotation System
Maps to CIE XYZ



CIELAB and CIELUV Color Difference Spaces

1 unit = "just noticeable difference" (1 jnd)
Lightness (L^*) plus two color axis
Function of XYZ of color plus XYZ of white



From Principles of Digital Image Synthesis by Andrew Glassner. SF: Morgan Kaufmann Publishers, Fig. 2.4 & 2.5, Page 63 & 64
© 1995 by Morgan Kaufmann Publishers. Used with permission.

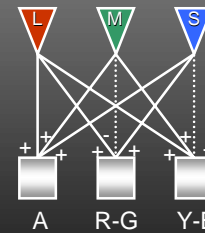
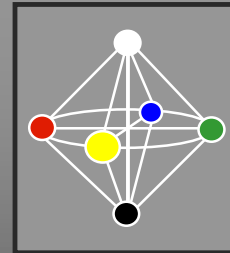
Opponent Color

Definition

- Achromatic
- R vs. G and B vs. Y axis
- First-level processing

History

- Herring, 1878
- Jameson & Hurvich (1955)



Fairchild, Figure 1-13

Color Vision
Leo Hurvich

Support for Opponent Color

Unique hues

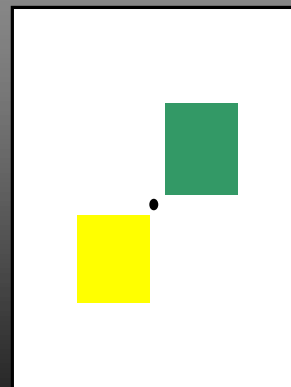
—No reddish-green

Afterimages

- Red-green
- Blue-yellow

Color vision deficiencies

- Red-green anomalies *
- Blue-yellow anomalies



Color Appearance Phenomena

Related colors

- Simultaneous contrast
- Spatial frequency

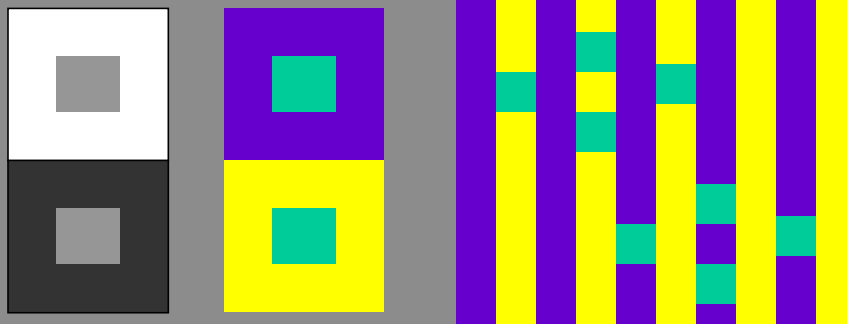
Adaptation

- Light/dark adaptation
- Chromatic adaptation

Perceptual and cognitive effects

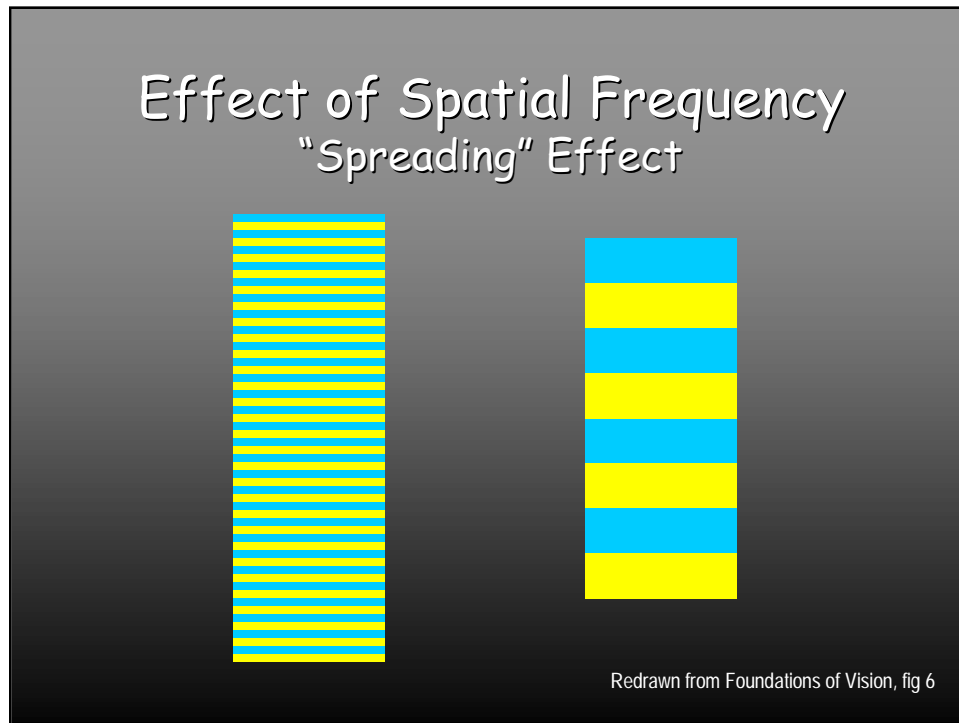
Color Appearance Models
Mark Fairchild

Simultaneous Contrast



"After image" of surround
adds to the color

Cognitive component
Identical patch and surround



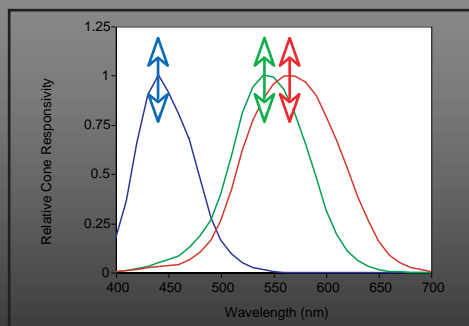
Chromatic Adaptation

- Change in illumination
- Automatic "white balance"
- Perceptual
 - Scale cone sensitivities
 - von Kries
- Cognitive
 - Discount the illuminant
 - "Object constancy"



From Color Appearance Models, fig 8-1

von Kries Adaptation



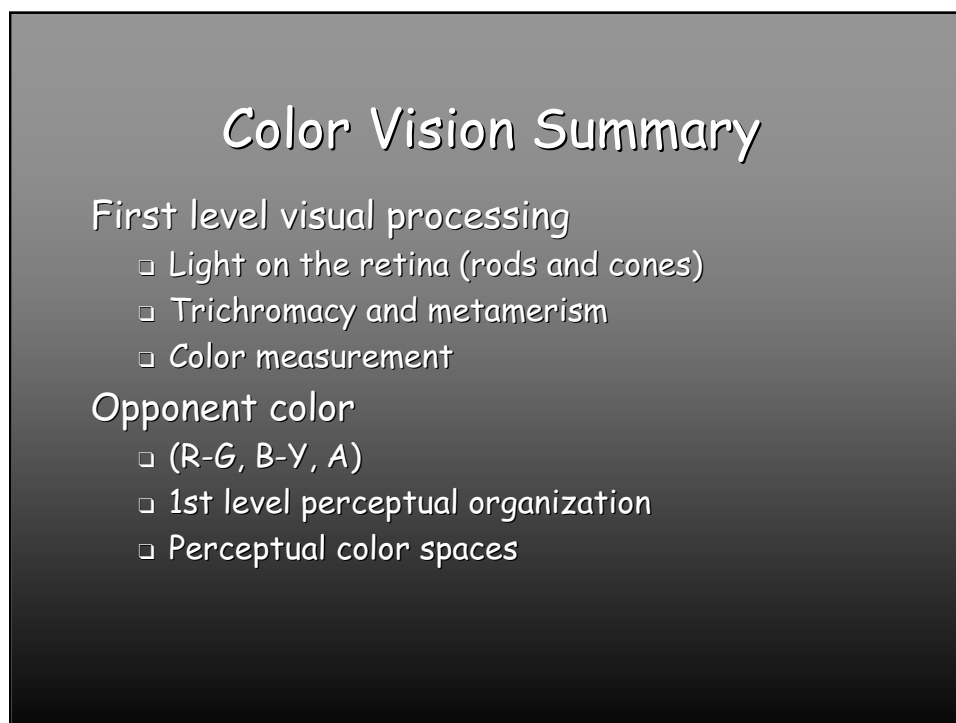
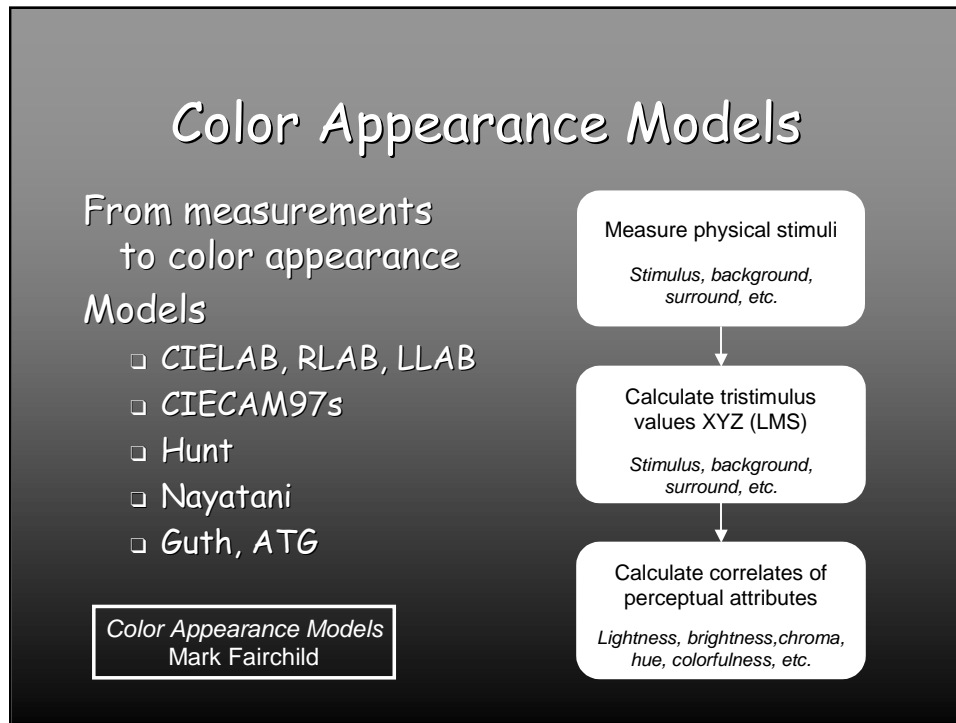
$$L_a = k_L L$$

$$M_a = k_M M$$

$$S_a = k_S S$$

$$k_L = 1/L_{\text{white}}, \text{ etc.}$$

Adaptation by scaling the cone response curves



Color Vision Summary

Related colors

- Simultaneous contrast
- Spatial frequency

Adaptation

- Light/dark
- Chromatic (von Kries)

Appearance models

Image capture

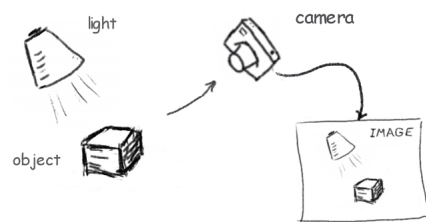


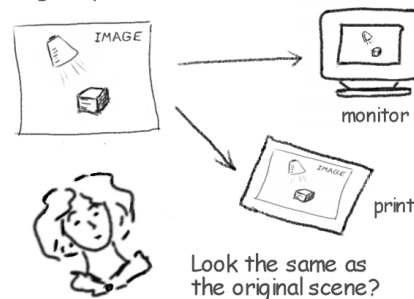
Image Capture

2D "picture" of scene
Array of pixels

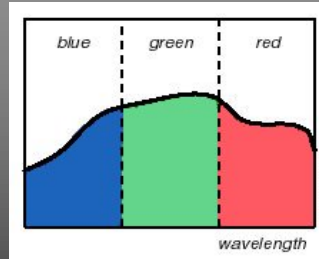
Image Reproduction

Display picture
Match original scene
Reproductions match too

Image reproduction



Color Reproduction



Principles

- Capture image as "RGB" components
- Reproduce each component
- Metameric match to the "original"

The Reproduction of Colour
Robert Hunt

Image Reproduction

Different media

- Additive: Video, displays, projectors
- Subtractive: Film, printing

Reproduce image appearance

- Nature to media
- Across media

Almost always an approximation

Reproduce Image Appearance

Tone reproduction

- Map the achromatic (brightness)
- Media limited with respect to nature
- Key to good reproduction

Color "correction"

- Originally make the primaries match
- Similar to RGB or CMYK balance adjustments

Device-Independent Color

Characterize with respect to a standard

- Take measurements
- Map to CIELAB or CIEXYZ

Represent device "gamut"

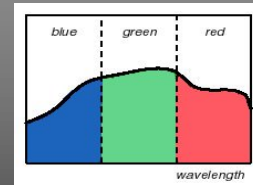
- All reproducible colors
- 3D volume

Basis of color management systems

Image Capture

Create R, G, B color separations

- View through R, G, B filters
- Filters act as CMF's
- Rarely colorimetric



Characterize by measuring patches

- Depends on input spectra
- If not colorimetric, then input-specific

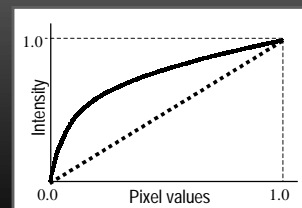
Image Encoding

Encode R, G, B components

- Pixel = amount RGB
- Digital data will be quantized

Linear encoding is not efficient


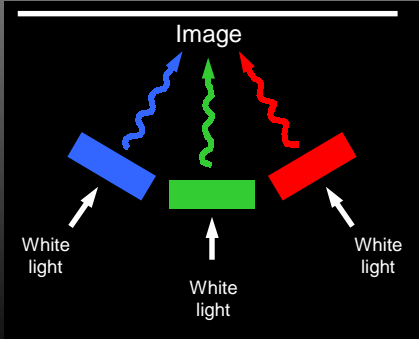
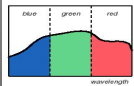
- 10 bits or more to eliminate contouring
- Density, companded intensity



Additive Reproduction

Combine red, green, blue lights


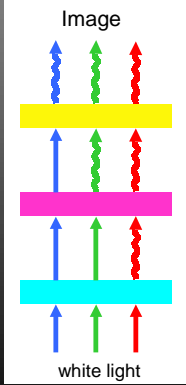
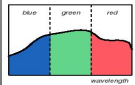

Primaries
 red
 green
 blue

Subtractive Reproduction

Filter white light to modulate R, G, B

Primaries
 cyan
 magenta
 yellow

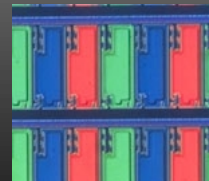
Additive Media

CRT Displays

- RGB phosphor dots and electron gun
- Intensity defines grayscale

LCD Displays

- Backlight and RGB filters
- Degree of transparency



Digital Projectors

Imaging elements

- LCD: light valve
- DMD: pulse encoded

Three elements

- Dichroic mirrors split light
- Overlay to combine

One element

- Color wheel
- Combine sequentially

Television/Video

Camera captures separations

- Standard RGB
- Comanded intensity
- Compressed to brightness + color (IYQ)

Reproduced on RGB display

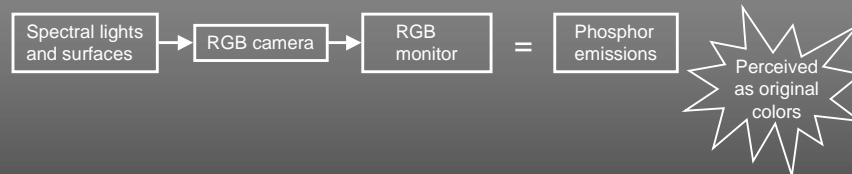
- Decompress and map to RGB voltages
- Create correct appearance

Details are all specified

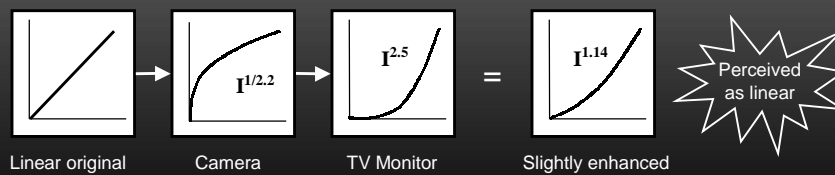
Digital Video
Charles Poynton

Television Pipeline

RGB Encoding



Intensity Encoding (ITF)



RGB is Linear Space

Similar to tristimulus values

Easy to characterize

- Measure the primaries
- Measure the ITF's
- RGB to XYZ is an invertible matrix

Monitors, LCD's: 3x3 matrix

Projectors: 4x4 homogeneous matrix

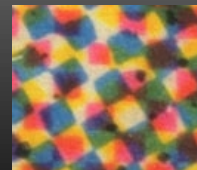
Subtractive Media

Photographic slides and prints

- CMY emulsion layers
- Density encodes grayscale

Ink on paper printing technologies

- CMY plus black (K) ink
- Halftone or dither patterns
- Some true grayscale
 - Inkjet multi-drop
 - Dye sublimation





CMYK Separations
 red = magenta + yellow
 green = yellow + cyan
 blue = cyan + magenta
 black for contrast



CMY is Not Linear

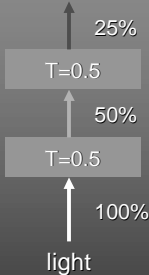
Filters multiply, not add

- $0.5 \times 0.5 = 0.25$
- Density = $\log(1/T)$
- 0 = clear, 3 to 5 = opaque

No simple transform to RGB, XYZ

Characterize by sampling

- 3D table of color patches
- Interpolate



Gamuts and Gamut Mapping

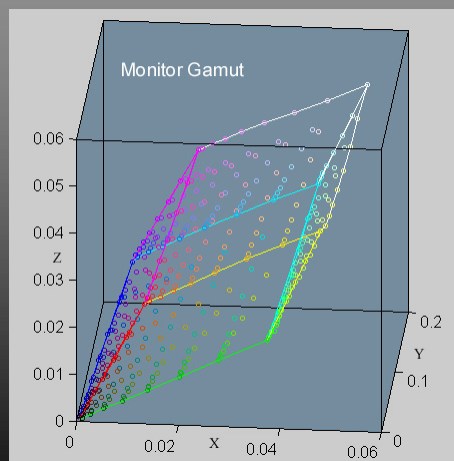
Gamut

- Set of all possible colors
- 3D volume

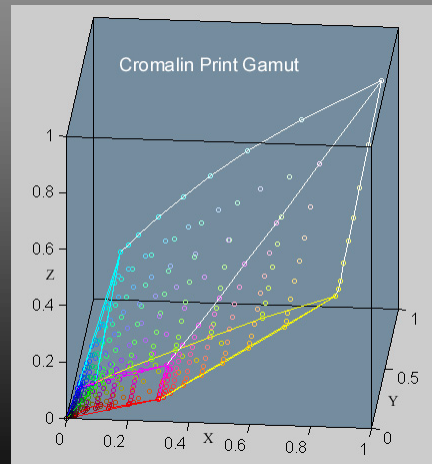
Gamut mapping

- Map out-of-gamut colors
- Follow the principles of image reproduction

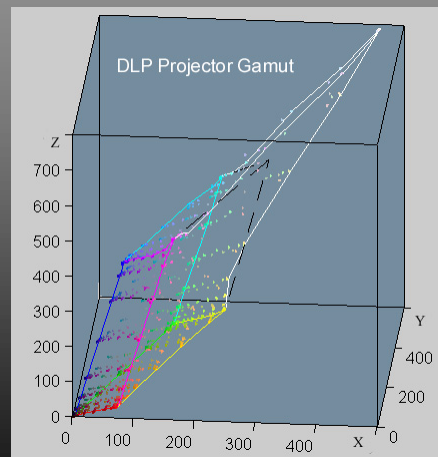
Additive System Gamuts



Subtractive System Gamuts



Hybrid Gamut (DLP)



Chromaticity Representation

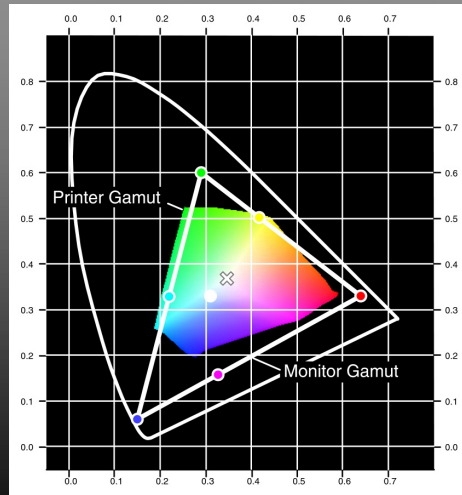
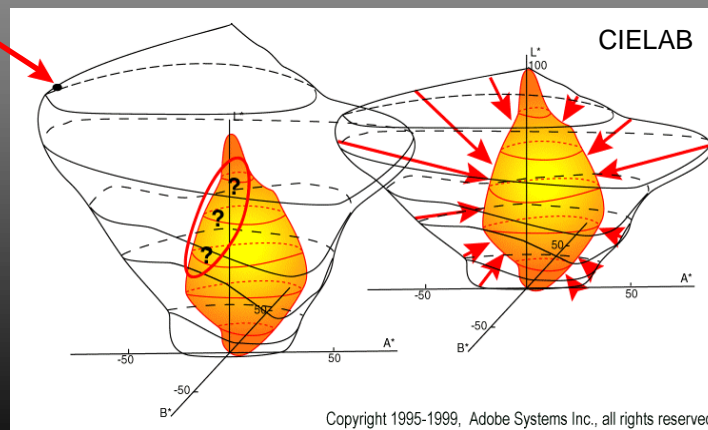


Image courtesy of ACM TOG

Gamut Mapping

Where does this color go?



Copyright 1995-1999, Adobe Systems Inc., all rights reserved

Digital Color Management

Device-independent color

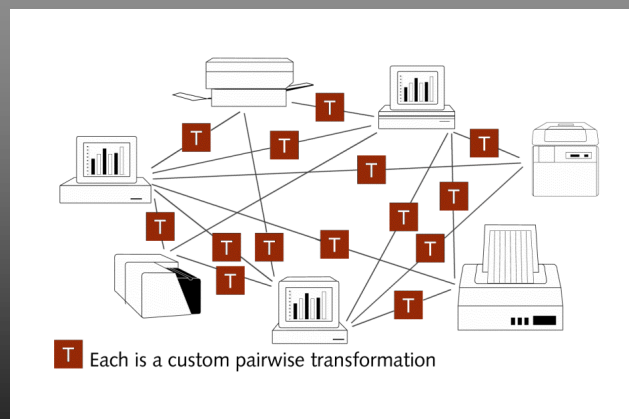
- Based on color psychophysics
- CIE standards and extensions

Color management systems

- Standard color specification
- Characterize devices (profiles)
- Make colors/images "look the same"

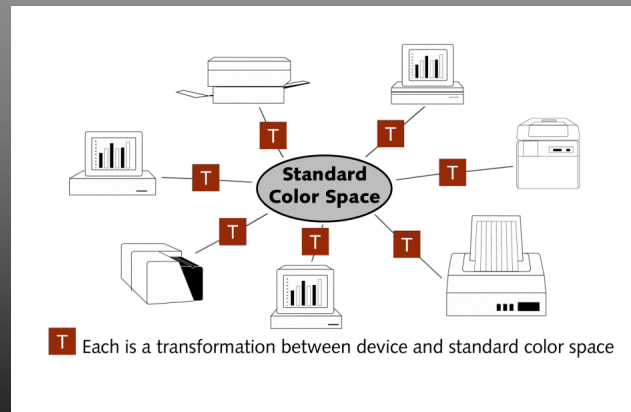
Digital Color Management
Giorgianni & Madden

The Problem



Copyright 1995-1999 Adobe Systems, Incorporated. All Rights Reserved.

The Solution



Copyright 1995-1999 Adobe Systems, Incorporated. All Rights Reserved.

CMS Issues

Profiles (calibration)

- Native color space to standard
- Requires color measurement
- Many variables = many profiles

Systems

- ICC standard profiles (www.color.org)
- Different CMS give different results

Gamut Mapping Issues

No crisp definition for "best reproduction"

Appearance models

- Current systems use CIELAB
- Next generation: CIECAM 97

BUT

- Appearance match may be impossible
- Extreme map is a redesign

Image Reproduction Summary

Image capture: RGB to pixels

Image reproduction

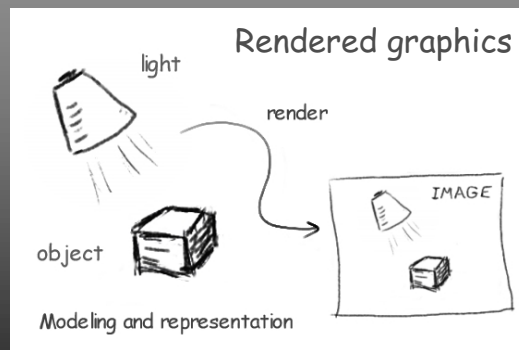
- Additive (RGB)
- Subtractive (CMY+K)

Digital color management

- Common color space
- Look the same...as possible

Rendered Graphics

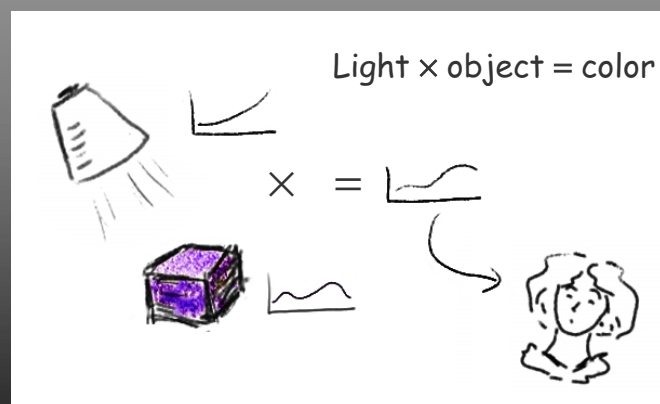
Virtual objects,
lights and textures
Rendered to produce
a visible image



*Illumination and Color in
Computer Generated Imagery*
Roy Hall

*Principles of Digital
Image Synthesis*
Andrew Glassner

Objects & Lights



*Exploratory
Color Playground*

Spectral Color

Lights and object colors

- Sampled functions
- Wavelength vs intensity or reflectance

Convert to tristimulus values

- Color matching functions
- Integrate

XYZ to RGB for display

RGB from XYZ

Let X_R, Y_R, Z_R be the CIEXYZ values for monitor R, G, B, etc.

Then:

$$[R \ G \ B] \begin{bmatrix} X_R & Y_R & Z_R \\ X_G & Y_G & Z_G \\ X_B & Y_B & Z_B \end{bmatrix} = XYZ_{RGB}$$

Invert matrix to get RGB from XYZ
Works for any linear, additive RGB system

Physical Models

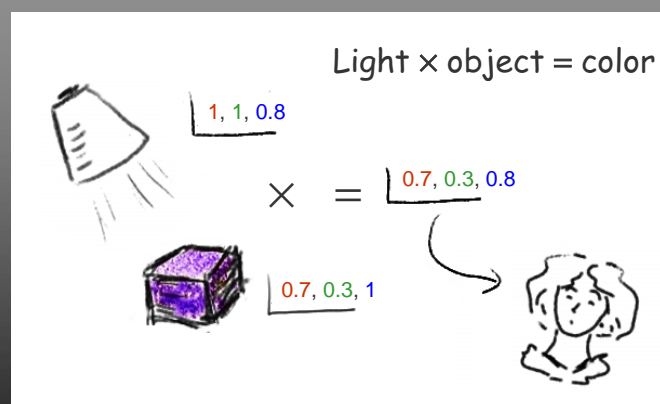
Advantages

- Realism
- Physical simulation

Disadvantage

- Complexity
- Expensive

Simplified Models



Based on RGB triples
Surface interactions also simplified

RGB Models

Simple extension of grayscale shading

- Red, green and blue intensity
- Works quite well for simple shading
- Inaccurate for complex models

RGB analogy

- Like color separations
- Like tristimulus values

RGB Accuracy

Accurately represents single color

Can't accurately represent interactions

- Lights with surfaces
- Reflections

Product of
Tristimulus values

≠

Tristimulus values of
Product of spectra



"Trichromatic Approximation..."
Carlos Borges, SIGGRAPH '91

Color in Nature

Reflective

- Highlights, textures
- Subsurface scattering, fluorescence

Shimmering

- Thin films make interference patterns
- Butterflies, soap bubbles

Scattered

- Fine particles
- Smoke, sky, eyes

Lights, rainbows

The Color of Nature
Murphy and Doherty

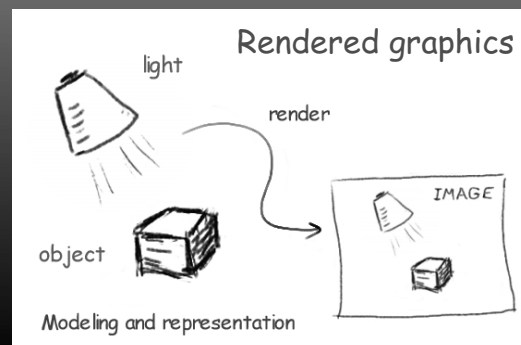
Display the Image

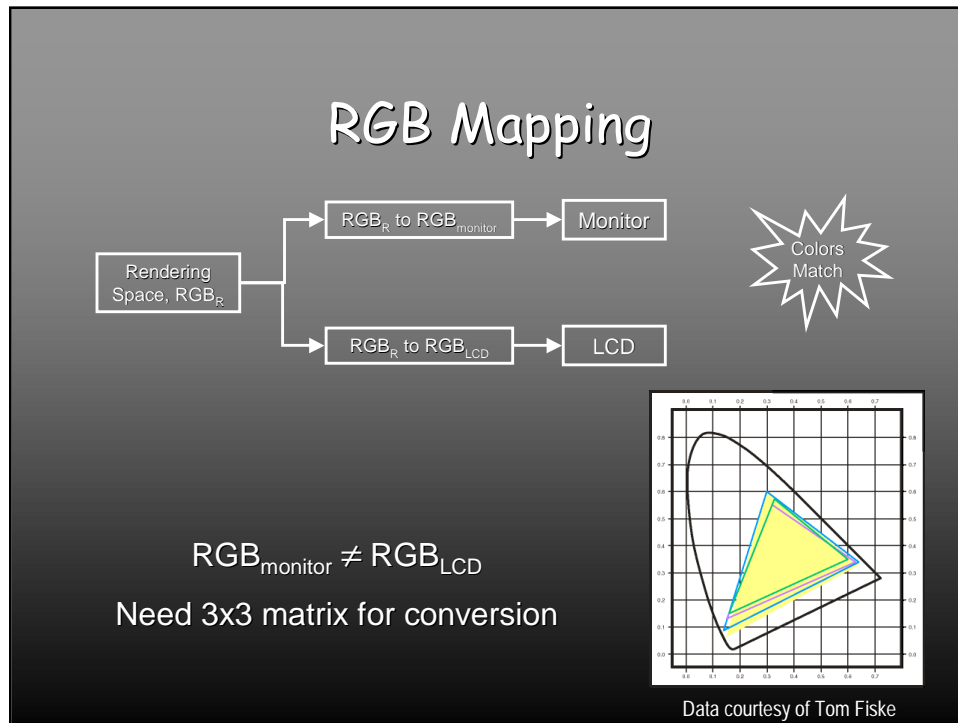
Rendering space

- Unbounded linear intensity
- Map to media gamut

Mapping parameters

- RGB mapping
- Intensity mapping
- Desired appearance





Intensity Mapping

Linear rendering space

Non-linear display system

- Display gamma
- "Gamma correction"

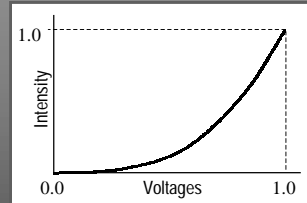
Desired appearance

- Bartleson & Breneman
- Tumblin and Rushmeier

The Gamma Problem

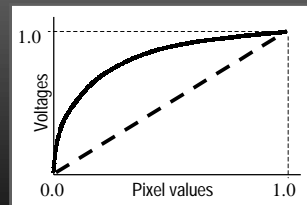
Device gamma

- Monitor: $I=A(k_1D+k_2V)^\gamma$
- Typical monitor $\gamma = 2.5$
- LCD: Nearly linear



OS Gamma

- Defined by operating system
- Inverse gamma curve ($I^{1/\gamma}$)
- "Gamma correction"



Display System Gamma

Product of Device and OS curves

- Divide Device by OS gamma
- $\gamma_{DS} = \gamma_D (1/\gamma_{OS})$

Display system gamma varies

- Different devices
- Different OS

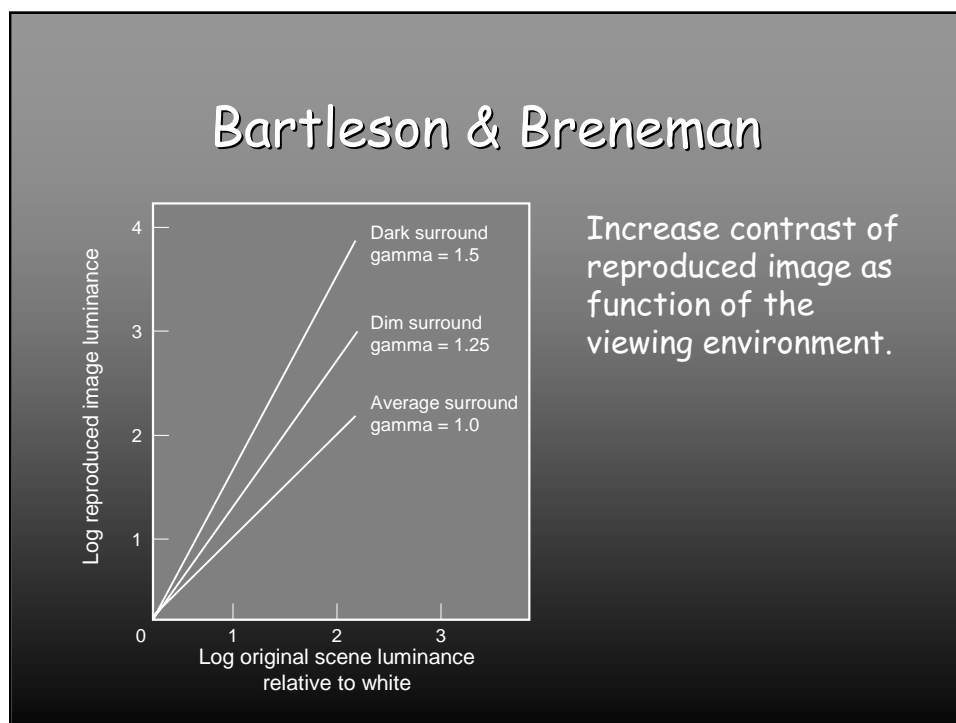
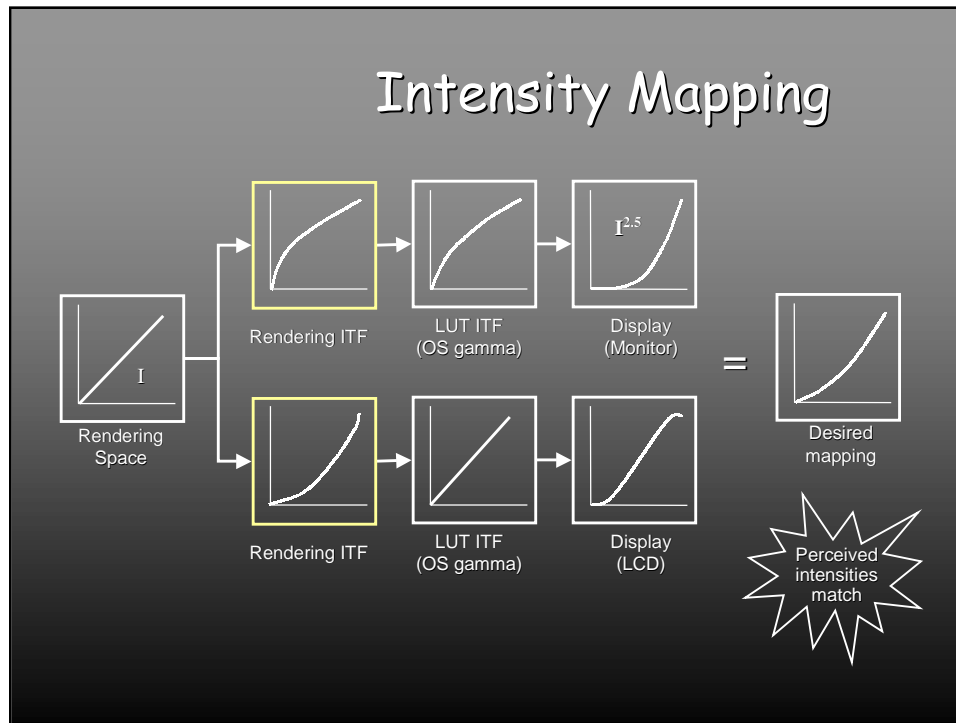
PC	Mac	SGI
1.0	1.4	1.7

Default OS Gamma

PC	Mac	SGI
2.2	1.6	1.3

Default DS Gamma

Viewing conditions also affect perception of "gamma"



Tumblin & Rushmeier

Tone reproduction operator based on human visual system

Considers

- Absolute brightness
- Adaptation
- Accurate display models

Resulting pictures more realistic

Rendered Graphics Summary

Simulate lights and objects

- Representation
- Create an image

Display (reproduce) the image

- Lightness and RGB mapping
- Gamut issues
- Appearance issues

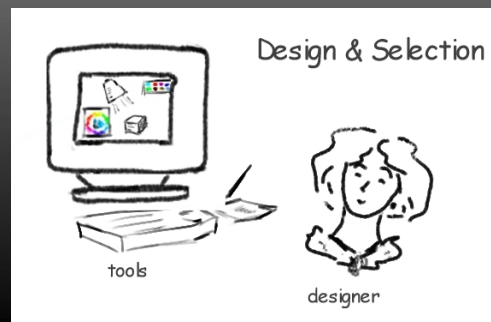
Design & Selection

Visual designer's view

- Color harmony, palettes
- Visual function of the color

UI designer's view

- Interactive tools
- Sliders and names



Principles of Color Design

Selection of groups of colors

- Visually appealing
- Send a message

Basic concepts

- Color terminology
- Color harmony
- Color palettes

Principles of Color Design
Wucius Wong

Color Terminology

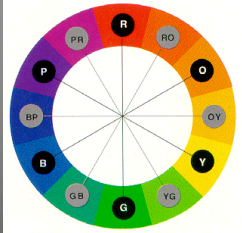
Hue

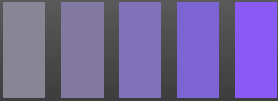
- Color wheel
- Primary, secondary, tertiary


Chroma (saturation)

- Intensity or purity
- Distance from gray

Value (lightness or brightness)







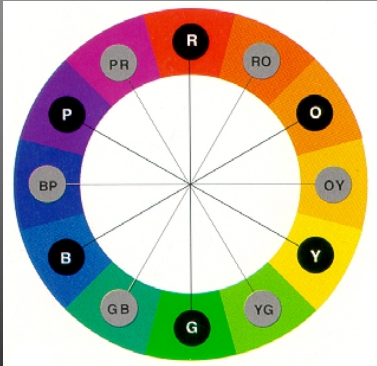
Color Wheel

Primaries
Red, yellow, blue

Secondaries
Orange, green, purple

Complement
Color opposite

Split complement
Two nearly opposite
Red, green-blue, yellow-green



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

Why Not CMY?

Red, yellow, blue

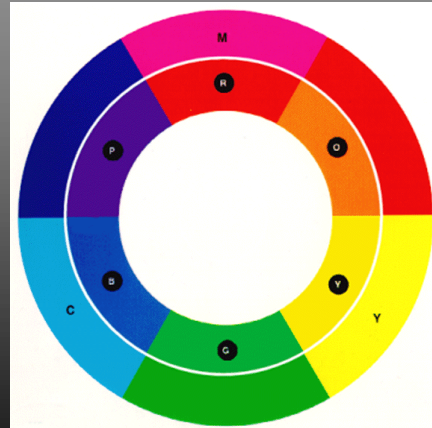
- Paint mixture
- Came first

Cyan, magenta, yellow

- Printing inks
- Transparent layers

Similar mixing behavior

Different gamuts



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

Tints and Tones

Tone or shade

- Hue + black
- Earth tones



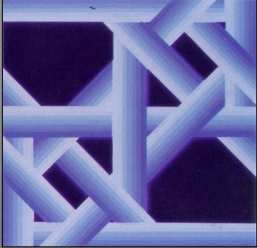
Tint

- Hue + white
- Pastels




Color Harmony


Apply contrast and analogy to hue, chroma and value




Vary chroma



Analogous hues



Vary value



Contrasting hues

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

Palettes

Color sets


- 2-3 hues
- Tints and tones

Define mood or message


- Warm, soft, etc.
- Elegant, professional, etc.

Specific harmony


- Primary, analogous, etc.




warm



elegant



analogous



primary

Palette Picker

Select by type

- ❑ Aesthetic (Powerful, friendly, etc.)
- ❑ Scientific (Complement, neutral, etc.)
- ❑ Harmonize with a specific color

Export color set

Color Harmony 2
Bride Whelen
www.lightdream.com



Color Selection Tools

Select points in a color space

- ❑ Device-specific spaces
- ❑ Perceptual spaces
- ❑ Sliders and tools of many forms

Color names

Little support for design principles

"Intuitive" Views of RGB

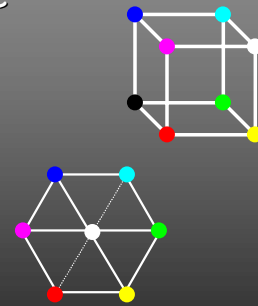
Transforms of the RGB color cube

HSV

- Hue hexagon (piecewise linear)
- Add black, add white
- Tints and tones

HSL

- H and S as in HSV
- Lightness more like perceptual spaces



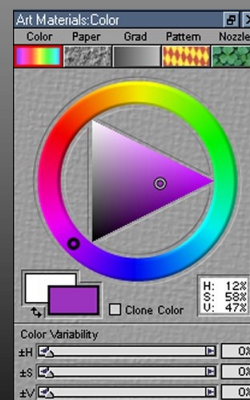
Interactive Tools

Common elements

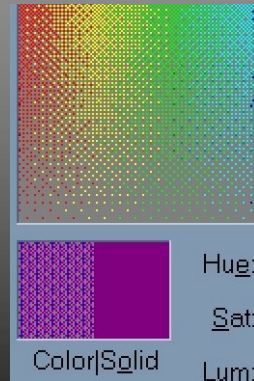
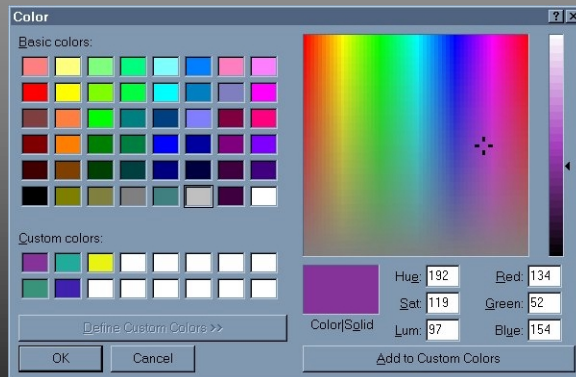
- Map 3D to 2D
- Interactive sliders
- Numerical values
- Simple palettes

Metadesign Painter

- Hue circle
- SV triangle
- HSV values



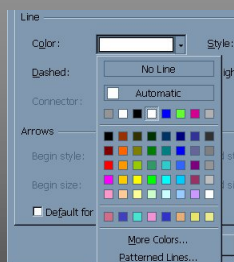
Netscape Navigator Microsoft Windows



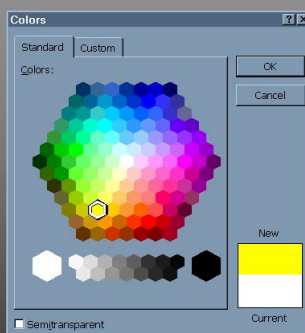
Standard and custom palettes
HSL and RGB selection
L slider + HS square

"Solid" mode for
text and lines

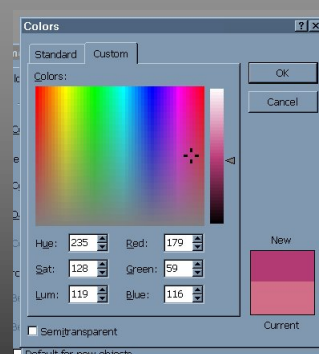
Microsoft PowerPoint



Basic palette
Includes "none"



Modify standard
HS hexagon + grays
New vs. current



Custom Colors
RGB and HSL
HS + L sliders
New vs. current

Jasc Paint Shop Pro

eyedropper

Hue circle + LS square
 RGB and HSL values
 Old and new patches
 Basic & custom palettes
 HTML code

Perceptual Color Spaces

Perceptually uniform spaces

- Munsell, Ostwald
- CIELAB, CIELUV

Digital examples

- TekHVC/TekColor
- Metapalette
- Canon Color Advisor

Color Names

Perceptual/linguistic fundamental

- Berlin & Kay, 1969
- Johan Lammens, SUNY 1994

Commercially used

- *Color, Universal Language and Dictionary of Names*, Kelly & Judd, NBS 1976
- Berk, Brownston & Kaufman, 1982
- Pantone Matching System®

black
white
gray
red
green
blue
yellow
orange
purple
brown
pink

Other Applications

HTML names

- Named RGB values
- 140 names (!)

X-Windows

- Color name database
- Binds name to value
- /usr/lib/X11/rgb.txt

Color	Hex #	Color	Hex #
Aqua	00ffff	Navy	00005d
Black	000000	Olive	5d5d00
Blue	0000ff	Purple	5d005d
Fuschia	ff00ff	Red	ff0000
Gray	5d5d5d	Silver	a8a8a8
Green	005d00	Teal	005d5d
Lime	00ff00	White	ffffff
Maroon	5d0000	Yellow	ffff00

Making Color Effective

Avoid clutter

Emphasize legibility

Accommodate

- Atypical color vision
- Color-deficient devices
- Cross-media rendering

“Using Color Effectively in Computer Graphics”
Lindsay MacDonald, CG&A, July 1999

Avoid Clutter

Pre-attentive label

- Count the 7's
- Too many colors spoils effect

Examples

- Maps and charts
- Colored text, logos

67491249754625
49608765723514
65067872614332
64761256127810
46723451215346
60723761428385

Legibility

Luminance contrast

- Hue alone doesn't make an edge
- Make legible in grayscale
- Dropshadows and similar tricks



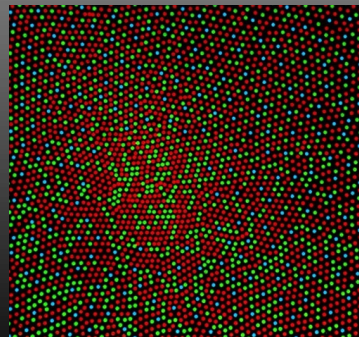
With drop shadows

The "Blue" Problem

"Blue" cones are sparsely distributed
Focus different than red and green cones
No blue cones in the center

Blue text can be
Hard to read

Different Focus
Different Focus
Different Focus
Different Focus



Fairchild, Figure 1-5

Accommodate the Viewer

Atypical color vision

- Minimize red-green encoding
- Duplicate all information
- Should "read well" in grayscale



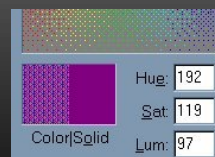
Color-Deficient Media

Monochrome media

- Luminance contrast
- Duplicate information

Dither and halftone patterns

- Texture and raggedness
- Use solid colors
- Default colormaps



Netscape Navigator

Design & Selection Summary

Many clever tools

- Selecting individual colors
- Generally device-specific

Missing

- Full support for design principles
- Palette selection and management
- Levels of indirection, functional colors

Finale

