handprint : color harmony & design

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color harmony & color design

Guidelines for color design are at the heart of artistic color theory (http://www.handprint.com/HP/WCL/color18a.html). But are those guidelines any more reliable or useful than an alert artistic judgment? Can we find better guidelines than those handed down from the 18th century?

To answer these questions we must explore four issues: (1) what we mean by the concept of *color harmony* among two or more colors viewed together how we decide whether color combinations are or are not harmonious; (2) whether *certain combinations* of color attributes (such as hue, lightness and chroma) consistently produce harmony; (3) whether these combinations can summarized as a *color theory* of visual harmony; and (4) how we apply this color theory to generate *principles of color design* specific design answers for specific design problems.

All that is too conceptual and abstract. So to start the discussion I use a painting by Paul Gauguin to illustrate , to show how an artist's color choices might be guided by "color theory" as it is commonly taught to artists, and why "color theory" fails to answer many important and specific design problems.

I describe the , which provide a widely accepted color terminology for types of hue groupings or hue contrasts. I present by Isaac Newton, Count Rumford, Rudolf Arnheim, Michel-Eugène Chevreul, Faber Birren, Alfred Munsell, the Optical Society of America and Antal Nemcsics to illustrate how these abstract systems are based on different color simplifications or one of .

Next I introduce the concept of color contrasts that take into account *all three* colormaking attributes (http://www.handprint.com/HP/WCL/color3.html#colormaking), rather than hue alone, and illustrate with a variety of "square in square" contrast demonstrations (http://www.handprint.com/HP/WCL/color4.html#chromainduct) how intense, pastel, darkened or grayed colors affect one another. In these comparisons I use *color nuance* to separate the effects of hue from the effects of lightness and chroma.

Based on this historical review and contrast examples, I present my own and explain how it provides many straightforward design principles in specific situations.

I am skeptical of any artistic "system", even my own. So I conclude with some commonsensical advice from the Victorian English critic , who reminds us to use color by following our personal artistic judgment.

basic issues in color design

We start with flyover of the color design process, to illustrate the "color theory" approach to color design and to clarify some color design problems.

A Painting Example. First, we need a concrete example of a finished color design. I suggest you choose your own favorite painting as an example, a painting you enjoy or love for its color or overall impact. As my choice, here is a *Bouquet de fleurs* (1897) from another businessman turned artist, a canvas in the Musée

Marmottan (Paris) that I visited one rainy summer morning many years ago.

a color bouquet from paul gauguin

This painting is composed primarily of warm scarlets and golds, contrasted starkly against dark browns and greens, with color variety provided by small accents of blue and green and the large area of greenish grays at bottom. The image is animated by the scattered red blossoms and floral clutter, which contrast with the rounded fruit and vase and the flat areas of wall and table top.

technique

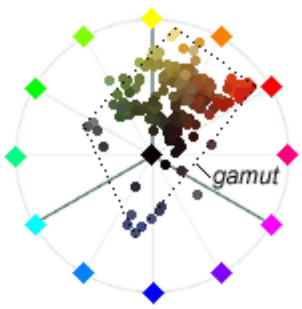
library of chromatic induction & contrast (http://www.handprint.com/HP/WCL/IMG/CICH/cich.html)

(http://www.handprint.com/HP/WCL/wtech.html)

The unsaturated, dark values are an important aspect of the design, as they make the scarlet flowers "pop" (appear by contrast relatively brighter and more saturated). All the normally bright or light valued colors, such as whites or yellows, have been darkened or muted toward grayish greens and blues, to emphasize this effect. The variety of paint impasto and brushstroke textures also contribute to the overall impact.

A Color Map. To clarify our color analysis, we first require a framework that permits the hue and chroma, or hue and lightness, in any painting to be accurately described. This framework would also allow the colors in different paintings, or in a visual style, to be summarized and compared.

My solution is a **color map**. This is made by measuring the hue and lightness of a large, systematic sample of single pixels from an electronic image of the painting, then plotting the location of these values inside a palette scheme (http://www.handprint.com/HP/WCL/palette1.html#scheme). (Lightness is more accurately recorded than chroma in an electronic image.) Here's what I get for 250 pixels sampled from Gauguin's painting:



(http://www.handprint.com/HP/WCL/colormap.html)

color map of the gauguin painting

250 single pixel measurements of hue angle and lightness sampled from a large format digital image; lightness is shown as distance from center (black) to circumference (white); 12 tertiary hues shown for reference

The main distortion that is introduced here is that **the image content has been discarded**. All the poetry of the original image has been chopped away: the bouquet has been shredded into compost. And this is the first insight into color design assumptions: most "color harmony" schemes adopt the Frankenstein premise that you can make a lively painting by stitching together bits and pieces of color.

In fact very hard to make the leap from compost to a bouquet, from an abstract color scheme to a specific assignment of colors to objects in an image one must also consider the value design, the style of representation, the size of the image, and so on. These are visibly important aspects of the Gauguin work, yet color design implies you must focus on the inherent qualities of colors in order to work out their "color harmony".

A Palette Scheme. The natural next step is to the inherent quality of paints. The color map is useful because it outlines the color space or gamut (http://www.handprint.com/HP/WCL/color13.html#gamut) of the painting. In any gamut, the most saturated, pure pigments or paints will appear at the extreme points or "corners" of the distribution of mixtures. So there is clearly a **scarlet** pigment in the palette, probably vermilion (mercuric sulfide, PR106 (http://www.handprint.com/HP/WCL/waterr.html#PR106)); there is also a **middle yellow** (either cadmium or chrome yellow), a **reddish blue** (cobalt or ultramarine blue), and a dark **green** paint. (This can't be judged from an image; it could be a bluish green pigment such as viridian, a convenience mixture such as cadmium green, or a palette mixture of the blue and yellow paints.) Unsaturated pigments within the gamut are harder to identify, but are usually indicated by heavy clusters or lumps of color within the color map. There are three of these, and they suggest **yellow ochre**, **burnt sienna** and **burnt umber** were included. Finally, a warm **white** was necessary for the light valued table top, and a **black** paint was probably used as well. So Gauguin plausibly used at least nine separate paints on his canvas. Based on the conjectural paint selection derived from the gamut of the color map, we can summarize Gauguin's palette as an abstract or idealized palette scheme (http://www.handprint.com/HP/WCL

/palette1.html#scheme).

(http://www.handprint.com/HP/WCL/colormap.html)

a plausible palette scheme for the gauguin painting

This example illustrates two important points: (1) the implementation of a color scheme depends on the available choices of pigments, dyes or colored materials (yarns, tiles) in the media that can be used to represent it; and (2) the use of a specific medium always defines a specific gamut, which produces unique limitations on the color relationships (saturation or purity of hue and value contrasts) between different hue categories.

Two new, important distortions are added here. First, **paints colors are treated as abstract hue categories** rather than as specific kinds of materials. We are no longer thinking in terms of **material colors** the unique colors produced by a specific color medium, but in terms of **concept colors** anchored with a generic color name *yellow*, *red*, *medium yellow*, *bluish red*, and so on.

It will be important later to distinguish concept and material colors: to do this, concept colors will be written in small capitals, as YELLOW or RED. Note that the concept colors used in color theory are typically **hue labels** that do not specify anything about the saturation, lightness or darkness of the color. The palette scheme cannot tell us if Gauguin used his paints as pure colors or "broke" them in various mixtures with each other.

The second distortion is that the **color proportions have been discarded**. We have no way of knowing, from the palette scheme, how much of each paint color was used in the original painting, or even what are the proportions among these colors that would give the best overall effect. We have the color ingredients, but no instructions for how to combine them in an image.

These omissions are potentially more serious than shredding up the image content to make a color map, because materials and proportions significantly affect our reaction to color, even when color appears in abstract textile designs or in the choice of wall, carpet and furniture colors in interior design.

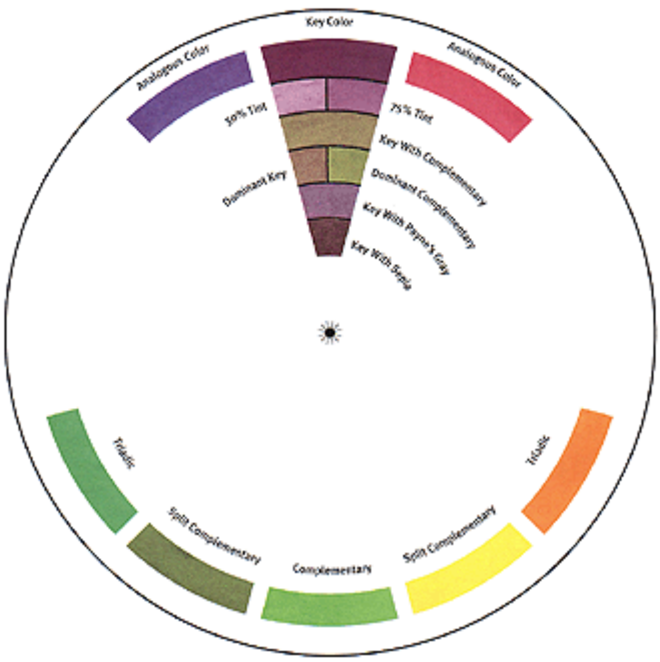
A Color Harmony. Now, how did Gauguin arrive at his specific selection of paints? The standard color theory answer is that he chose a color design for the painting based on **color harmony and contrast**, used this design to guide the choice of paints, and then applied these paints in ways that preserved the intended harmony and contrast while matching his intended visual design and the appearance of the still life he was painting.

OK, so how did he get the color harmony? Here "color theorists" simply lay down the dogma that certain colors do or do not produce harmony or contrast; most justify these color relationships in terms of relationships. In the outcome, the painter simply chooses from among a group of predefined color patterns or *color schemes* or analogous, complementary, triadic, etc. The scheme is a kind of convention or recipe intended to ensure pleasing or effective color effects.

the split complementary color harmony

One might expect that these color recipes are fairly specific, but in fact "color theory" makes them completely abstract *analogous colors, complementary colors* and so that are independent of which hues we are talking about. So long as you talk about these **color relationships**, it does not matter which specific hues they refer to.

A perennial expression of this disregard for specific hue relationships is the circular *color calculator,* which shows the harmonious or contrasting color combinations for any specific **key color** or anchor color you might choose. The example below, the **color systems dial** devised by the workshop watercolorist Zoltan Szabo (http://www.handprint.com/HP/WCL/book3.html#szabo) shows all the theoretically related colors for any categorical key color (red violet in the example) that the artist might choose.



zoltan szabo's color systems dial

the key color (top) is red violet

The general idea is that the painter can spin the dial to find appropriate combinations of colors for the specific key color under consideration. Note that the *windows* in the card, the relationships among abstract color categories, are the actual "color harmony": the hues that appear through the window are just interchangeable tokens.

These color calculators always remind me of the circular slide rule wielded to hilarious effect by Dr. Strangelove. They are, incidentally, an idea first proposed by J.W. von Goethe (http://www.handprint.com/HP/WCL/book3.html#goethe) who imagined *"a moveable diametrical index in the colorific circle"* to identify complementary color pairs.

But what happens if we apply this color dial logic and "spin the hues" of Gauguin's painting? The illustrations below shows what happens if we rotate all the color relationships on the "color calculator" by a single step toward magenta or toward green.

a "color systems dial" change in the gauguin color scheme

all hues shifted by one tertiary hue step toward magenta (left)
or toward green (right)

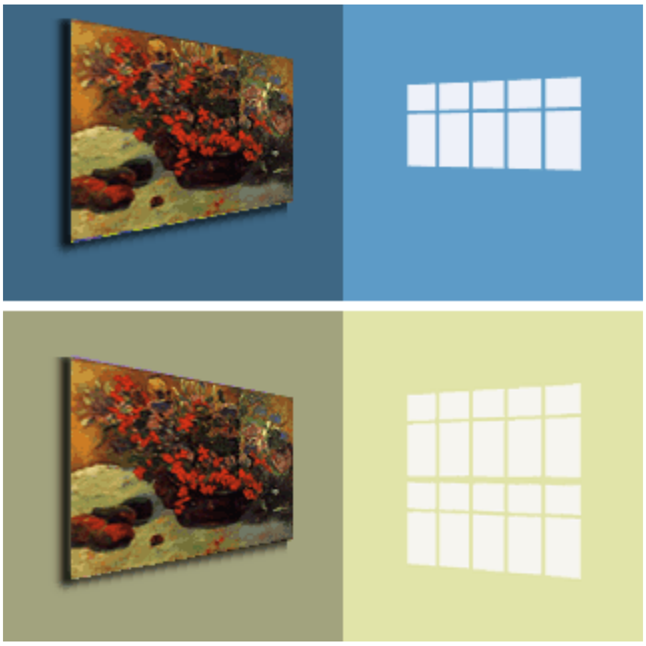
Eeek! Clearly, this is not right. By shifting the colors farther toward red, we've traded the potent contrast between scarlet and umber for the much weaker contrast between red and maroon, collapsing the color depth as a result. Alternately, by shifting the color emphasis toward green, we have created a sickly light and an unpleasant orangish yellow for the blossoms. Both images are less pleasing than the original.

This is why the "color theory" suggestion that you "spin the colors" is typically not useful: the peculiar types of contrasts, color changes and color relationships that appear in one hue area of the hue circle often do not apply in other hues, or a different lightness or saturation. The "complementary" contrast between purple and green is almost restful, the contrast between orange and cerulean is cheerful, the contrast between yellow and ultramarine is stark but the contrast between spectrum red and greenish blue is downright hostile.

By reducing specific, unique color combinations to abstract, spinnable color relationships, "color theory" achieves perhaps the most remarkable feat of all: it discards color itself, and only considers contrasts or similarities.

A Viewing Context. There is a final problem that rightfully should fall within the scope of "color theory", and that is the appropriate combination of colors in an environmental setting for example, the best choice of context in which to display a painting, or the best choice of painting to complement a specific architectural space or that trendy couch you've bought at Roche Bobois.

According to Kenneth Burchett, the traditional discussions of color harmony equate it with concepts such as *order, configuration, interaction, similarity, association* and *area*. in other words, **context**. In the simple example below, we've bought a nice print of the Gauguin painting, but find that the context in which we display it affects our sense of its color harmony.



gauguin's painting in two different rooms

How do we decide which setting works better, and what reasons do we have for the decision? Presumably if we have a theory of color harmony that really works, it would be able to explain the harmony or clash between colors across object boundaries between a painting and a wall, or a couch and a carpet.

What is Color Harmony, Anyway? Which brings us to the most fundamental question of all: how do we define color harmony? In this page I argue that:

Color harmony is the manipulation of lightness and chroma within a given selection of hues so that all colors contribute to an intended visual effect.

OK ... so what visual effect? We must stipulate at least four **criterion contexts** that determine whether color relationships are satisfactory or not, and each context implies different considerations in color design:

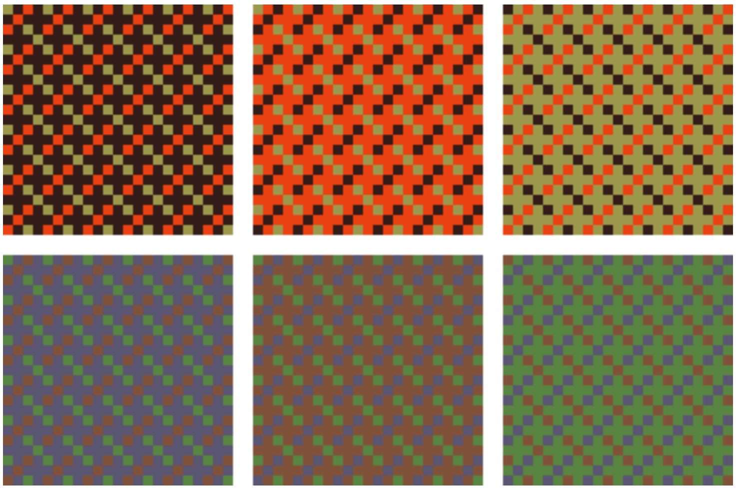
Pattern: the effect of color combinations to preserve the overall clarity of a figure/ground pattern, or alternately to blend visually into a specific visual mixture or texture: the *legible* effect of the color choices.

Object: the effect of the color combinations to produce visual cohesion ("goes together") or contrast ("stands out") within a single designed or significant object, such as a book cover, vase, painting or the apparel worn by the person: the *cohesive* effect of the color choices in relation to the environment.

Representation: the effect of the color combinations to produce a pleasing overall effect within a representational image, such as a photograph or painting: the *pictorial* effect of the color choices.

Environment: the cumulative effect of all material colors and light colors visible in a place, setting or environment, natural or engineered, architectural or mechanical (such as the cabin of a car), which combine to create a visual mood, local atmosphere, task setting or spatial effect: the *ambient* effect of the color choices.

These four criteria **PORE** in acronym do not lead to the same conclusions about color contrast. For example, here are the principal color contrasts in the lower left or upper right quadrants of the Gauguin painting, presented in a simple textile contrast pattern (http://www.handprint.com/HP/WCL/IMG/CICH/cich.html#textile) that displays the relative dominance, contrast and visual mixture among three colors.



textile patterns using gauguin's color choices

in area proportions 10:11:30 (right diagonal:left diagonal:background)

These patterns reinforce what we conclude by looking at the painting: (1) the scarlet, umber and yellow gray in the lower left of the painting (diagram, top row) are used to produce a strong visual contrast between the blossoms and the rounded forms against their backgrounds, and this contrast depends primarily on the dark umber separating the dull yellow from the scarlet (left pattern); and (2) the green, purple and mauve in the upper right of the painting (diagram, bottom row) are used to reduce contrast, which pushes these colors into the background and provides a cool color contrast to the predominantly warm hues of the painting.

However, if we evaluate the colors as textile designs, other issues become more important. What is the overall color of the design when seen from a distance is it dark or light, green or brown, warm or cool? How strongly does one color dominate the other two? What is the dominant visual pattern that results from all three colors combined left diagonal lines, right diagonal lines, a diagonal mesh, or a field of crosses? Which pattern and average color works best in the object, fabric or environment in which the colors are used?

If we change the context in which color relationships are judged, we are likely to prefer different color combinations for different reasons. The optimal color combinations and our reasons for preferring them change together.

Toward a Natural Color Harmony. What emerges as the basic issues in color harmony and color design? An important first step is a vocabulary to distinguish the different aspects of color we are talking about:

material color - the composition of light reflected from a surface or emitted by a light; always precisely defined by a spectrophotometric curve, but influenced by surface qualities of materials or the light absorbing qualities of light transmitting media.

visual color - the conscious sensation of color, viewed in a specific visual context under a specific level of illumination; always approximately defined by the colormaking attributes, plus luminance: this includes *appearance color* visual colors induced by viewing context.

concept color - color treated in the abstract or as a "pure" color that cannot exist in materials, usually as a category of colors denoted by hue label (primary BLUE) or by some other generic attribute (all SHADOW COLORS, all TINTS).

I argue that a useful and modern theory of color harmony and color design must include:

A compact summary of the necessary and sufficient principles of color perception, and including the effects of luminance and illuminant on color, stated as generalizations about harmony, contrast and dissonance;

The visual perceptual principles adapted as necessary to represent the capabilities and limitations of specific colored materials or lights stained glass and architectural illumination systems; dyes and pigments used in paints and inks applied to paper, photographic emulsions, canvas, textiles, plastics and ceramic glazes; electronic phosphors and lights used in televisions and computer monitors;

The use, application, purpose or significance of the colored artifact;

The viewing context or situation in which the colored artifact is encountered.

This page amplifies on these issues and concludes with an outline of my own "natural color harmony". Though incomplete, I believe it clearly illustrates the general direction in which any color theory must progress.

Some interesting color management or color analysis tools are now available online. **Kuler** is available from the Adobe website (http://kuler.adobe.com/). A fun online application to decompose electronic images into color swatches is available from the Colr.org (http://www.colr.org/) website.

Summary of Key Themes. Most traditional theories of color harmony prescribe the manipulation of two colormaking attributes while holding a third attribute constant; in this respect the hue mixture theories of Newton and Arnheim are primitive, despite their conceptual elegance.

Looking back across three centuries of color exploration, we can glean the following twelve principles from the historical study of color harmony:

1. Color harmony is traditionally defined as (1) proportions or ratios between fundamental color qualities (such as "primary" colors); (2) straight line samples drawn within a color space, the lines being divided into scales of equal or geometric color intervals; or (3) consistent relative locations around the hue circle (in particular, analogous and complementary hues).

2. Colors harmonize when they are variations within the achromatic grayscale (*achromatic harmony*).

3. Colors harmonize if they are variations in lightness and chroma within a single hue (*monochromatic harmony*).

4. Colors harmonize if they are variations of constant saturation across lightness within a single hue (*shadow harmony*).

5. Colors harmonize more, the smaller the hue difference between them (*analogous harmony*).

6. Colors harmonize more, the smaller the chroma difference between them, regardless of lightness or hue (*chromatic harmony*).

7. Colors harmonize if they are the same lightness and chroma, regardless of hue (*nuance harmony*).

8. Colors harmonize more, the greater their average lightness, regardless of hue (*brightness harmony*).

9. Colors harmonize more, when there are moderate but not extreme lightness differences among them (*lightness variety*).

10. Colors within a perceptual color space assort best if they are selected to lie on a single plane oriented at any angle to the lightness and opponent hue dimensions (*plane harmony*).

11. Colors harmonize more, when lighter valued and/or more saturated colors occupy a smaller visual area than darker and duller colors, in proportions equivalent to the degree of color differences among them (*color proportion harmony*).

12. Colors harmonize less and contrast more the larger the hue difference between them (*hue contrast*).

13. Colors contrast most pleasingly if they are complementary hues (*complementary contrast*).

(http://www.handprint.com/HP/WCL/IMG/OSA/index.html) click the image for a library of the OSA UCS color system

At the same time, we can identify five unresolved issues across theories of color harmony:

Material or Visual Color? - Should color harmony be defined in terms of material color mixtures (Arnheim, Birren, NCS), or visual color mixtures (Newton, Chevreul, OSA-UCS)? This is most significant when regulating chroma and lightness contrasts.

Similarity or Contrast? - Are colors harmonious because they blend well (Chevreul), or because they contrast effectively (Munsell)?

Subjective or Conceptual? - Should color harmony be defined according to subjective criteria (pleasant/unpleasant, attractive/unattractive) or formulaic, rational criteria (relative area, primary color combinations, colors within a scale, equality in lightness or chroma)?

Symmetrical or Irregular Geometry? - Should conceptual color harmonies be defined in terms of a colorant geometry (circle, sphere, triangle, cube, double cone; Chevreul, Arnheim, Birren, NCS) or should it be defined within a perceptual geometry (cylinder enclosing an irregularly shaped perceptual space; Munsell, Coloroid, OSA-UCS)?

Invariant or Contextual? - Should harmony be defined as an invariant quality of color combinations that is completely independent of the situation in which colors are viewed or the purposes for which the color is used (Rumford, Arnheim, Munsell)? Or should color harmony depend on the viewing context or functional use of color, so that colors that are harmonious in one situation may not be harmonious in another (Birren)?

concepts in natural color harmony

Now that we have in hand the common artistic language of , and have given thoughtful consideration to seven previous theories of , we can approach the task of formlating a truly modern, practical and effective theory of color harmony and color design. For reasons that I'll make clear later, I call these principles a **natural color harmony**.

This section introduces the fundamental *concepts in natural color harmony,* which are the concepts and terms that must underlie any accurate discussion of color. The next section develops these concepts as *principles of natural color harmony,* or a basic framework for understanding and applying color.

A Definition of Color. To begin with, what do we mean when we talk about color? As explained in the page on the Basic Forms of Color (http://www.handprint.com/HP/WCL/color4a.html):

Color is a contextual interpretation of surfaces illuminated by light in space.

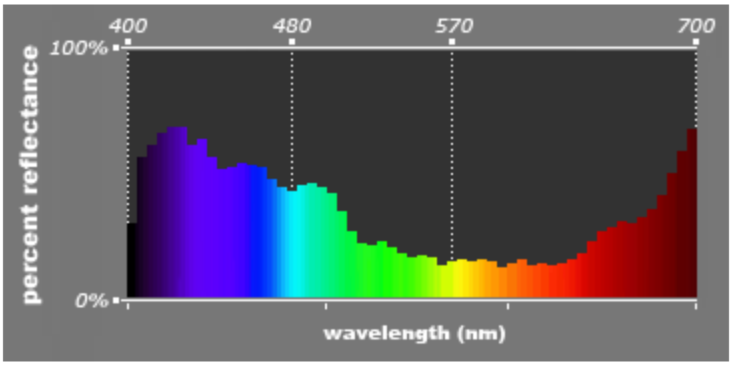
We do not experience color as an abstract sensory quality but as an inherent quality of objects situated in the physical world.

As I will illustrate below, color depends to a great extent on our implicit assumptions about the quantity and color of light in the environment, the direction light is coming from, the locations in three dimensional space of the objects that the light illuminates, the contrasts created in light shadowed or reflected by these objects, and the appearance of these object colors in comparison to a white surface. All these features are combined in what amounts to an automatic, unconscious and highly sophisticated *interpretation* of the real world context in which we see things.

I emphasize the concept of "interpretation" to prepare the idea that color is not something that is "in" the light or "in" the surface of objects or even "in" the response of our **L**, **M** and **S** photoreceptors. **Color is in the mind of the viewer**. This frees us from thinking of colors as having fixed attributes, and requires that we see colors as mediating or clarifying the dynamic relationship between the physical environment and our conscious interpretation of it. Colors resemble ideas more than they resemble sensations; they are *perceptions* ideas in the guise of sensations.

Three Kinds of Color. Despite the previous definition, it is perfectly sensible to talk about a "color" of paint or a "color" that we imagine rather than see. One of the difficulties in talking about color is that color seems to exist in several different forms (http://www.colour-journal.org/2009/4/6/09406article.htm). Three of these are most important:

material color is the mixture of light wavelengths emitted by a light source, or transmitted by a filter or other semitransparent medium, or reflected from an opaque material such as paint, ink, dye, photographic paper or many kinds of material surfaces. This defines color very narrowly, as a *physical stimulus* that we examine without any consideration of the context around it.



a reflectance curve

showing the percentage of incident light (vertical scale) that is reflected at each wavelength (horizontal scale) within the visible spectrum (400 nm to 700 nm)

Material color is exactly specified as a spectrophotometric curve (http://www.handprint.com/HP/WCL/color3.html#reflectance) (diagram, above), which can be measured in lights, filters, surfaces and colored substances such as pigments, inks or dyes. When measuring material color, the principal assumption is that the surface attributes of the material (including color unevenness, texture, *gloss* or mirrorlike reflectivity, iridescence, and translucency) do not significantly affect the spectrophotometric measurement.

visual color is a perception of a material color in a specific viewing context usually the color of a physical surface viewed in a specific place under a specific intensity and color of illumination. Visual color literally does not exist outside individual consciousness. It is personal, immediate, and always embedded in a context.

There is an enormous body of evidence to show that color experience is remarkably personal: it varies significantly across individuals, for a variety of reasons (genetics, age, experience). In addition, the same material color can appear as very different visual colors, depending on the light environment and surrounding colors where it is viewed. As a practical matter, then, the connection between a material color and visual color can be highly variable across individuals and viewing contexts.

Although visual color is personal, it does not have to be private. We can fairly reliably communicate visual color to other people through a variety of *color specification strategies*. For these to be effective, five conditions must be met when a material color is visually examined: (1) distractions caused by the surface qualities of the material color (such as color irregularities, surface reflections or iridescence) are eliminated or minimized; (2) the color is illuminated to approximately daylight brightness; (3) the illumination is both "daylight white" and broadband (i.e., the light includes all visible wavelengths at roughly equal energy); (4) the color is displayed against a medium gray background; and (5) the viewer's eye is accustomed or *adapted* to the background color and intensity of the illumination.

When these conditions are met, visual colors can be specified by mathematically translating the material color (the) into a color appearance specification on the three *colormaking attributes* (); or by finding the best visual match between the material color and the material color samples published as a standard *color atlas*; or by matching the material color to a color sample defined as a color "address" in a color reproduction system (such as the code "#336699" in the digital RGB color space or the formula "30-50-15-5" in the Pantone CYMK system). Note that these are not "different kinds" of color, but rather different ways to specify a standard visual color or a material color as the stimulus standard for the visual color.

conceptual color is color as an abstract concept, a sensory memory, a color label that calls to mind a visual or material color that is not present as a physical exemplar or as a visual perception. It is color defined primarily through language, memory, custom and habit.

Conceptual colors can be communicated as single color words (*auburn, chartreuse*), compound color descriptions (*brilliant dark blue*), the average color of a variable environmental stimulus (*sky blue, sea green, cherry red*), a color in color theory (*primary blue; "yellow* and *blue* make *green*"), an imaginary color ("no paint can be a *pure red*") a metaphorical color ("a *golden* sunset"), and much more.

Compared to both material colors and visual colors, conceptual colors are simplifications in three respects: (1) they are *categorical colors* that apply equally to many different kinds of material or visual color (*blue* can refer to eyes, skies, berries, plastics, flowers, textiles, ceramics, paints, stained glass, photographic emulsions, television screens and lakes); (2) they can refer to colors that are unknown to the person to whom the color is being described ("*yellow* is the color of my true love's hair"); (3) they disregard variation produced by individual differences in color sensitivity and viewing conditions (a lawn viewed at twilight is still called *green*); and (4) they assume that color descriptions mean approximately the same thing to all people. These simplifications make conceptual colors very useful in the general framework of language, but extremely troublesome as the basis to talk about color to any specific purpose.

It is extremely helpful to keep in mind the differences between material, visual and conceptual colors when thinking about color across the many topics in color thoery.

Three Visual Color Attributes. As , all *visual* colors can be minimally identified in terms of three basic attributes:

brightness/lightness. These are the color attributes directly related to the luminance of a color area, perceived either as an emitting light (that is, a surface that shines more brightly than a pure white) or as a reflecting surface, as .

hue. This is simply the "color" in color, the identifying chromatic content separate from variations in luminance. As , hue is conventionally diagrammed as a hue circle. Hue can always be exactly defined as a single wavelength of spectral light, or (for violet hues) either as the mixture of single "red" and "blue" wavelengths or as the complementary "green" hue that is directly opposite on the hue circle.

hue purity. *Hue purity* is my term for the third dimension of color, which been defined many different ways (http://www.handprint.com/HP/WCL/color3.html#colormakingchroma) across the past two centuries of color research the point being that "hue purity" is not specific as to how this third attribute is defined.

In terms of visual color, hue purity can be reduced to three distinct concepts:

colorfulness is the proportion of "pure hue" or pure chromatic reflectance (**C**) in a color, as a proportion of the sum of the pure chromatic content plus any *white* (**W**) reflectance and/or *black* (**K**) absorptance, when the color is *viewed in isolation,* without compensating for the illumination on the color. As a conceptual formula:

colorfulness = C / (C+W+K)

Colorfulness is equivalent to the "pure color" component in every , which defines colors as a mixture of pure color pigment, white pigment and black pigment. It is therefore the quality of hue purity that is most analogous to material color (as). We only perceive colorfulness if we compare the color to an imaginary "pure" color,

chroma is the relative amount of chromatic content absorbed by a color in comparison to the relative amount of luminance absorbed by the color.

The quality of colorfulness in surface colors, including paints and inks, perceptually increases with increasing illumination: all surface colors appear to darken or blacken under dim light, and even dull colors appear to increase their chromatic content in sunlight. To remove this sensitivity to illumination, chroma evaluates the color area by comparison with a "white" surface under identical illumination (diagram, right).

In chroma, the standard used to define "relative" for both chromatic and luminous content is a pure white surface *under the same illumination* as the colored surface. The comparison is just the difference between the two relative quantities. As a conceptual formula:

$$chroma_c = (RGB_c / RGB_W) - (L_c / L_W)$$

where the subscripts $_{\mathbf{c}}$ and $_{\mathbf{w}}$ refer to attributes of the colored and white surfaces, **RGB** represents the separate trichromatic color signals or stimulus measurements, and **L** is the *luminance* of the two surfaces.

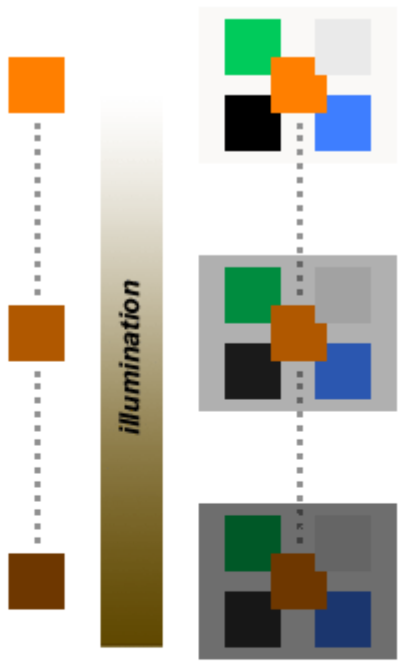
The logic of this concept is not difficult. A "white" surface is two things at once: it is a balanced signal among three different chromatic outputs, for example the **L**, **M** and **S** cones or the **XYZ** tristimulus values; and it is also a source of luminance. A colored surface is an *imbalanced* signal among three different chromatic outputs, but it is also a source of (relatively darkened) luminance. To define the chroma, we first define the proportion of luminance in the colored surface compared to the white surface, then we define the proportion of matching chromatic outputs between the two surfaces. If the chromatic proportion is either greater than or less than the luminance proportion, then the chromatic outputs are different from the chromatic outputs in a white (colorless) surface, meaning that chromatic content is present.

saturation is the chromatic content of a color judged (for lights) in relation to its own brightness, or (for surfaces) in relation to a gray or white of equal lightness under equal illumination. As a conceptual formula:

$$saturation = chroma_c / brightness_c$$

Saturation is entirely a perceptual quality, since both the chromatic content and brightness/lightness are visual color attributes. That is, we cannot use luminance to define saturation, only the perception of *relative luminance* as brightness or lightness. In particular, the saturation of an unfiltered light does not change if we make it brighter or dimmer, and the saturation of a surface color does not change if we increase or decrease illumination on it for example, surfaces in sunlight and in shadow have the same saturation, even though the shadowed surface is much darker.

Material colors can be described in terms of the three colormaking attributes by means of the measurement technology colorimetry (http://www.handprint.com/HP/WCL/color6.html#colorimetry). This requires (1) measurement of the emittance or reflectance profile by a spectrophotometer, which captures the intensity of light at each wavelength; and (2) the transformation of the measured wavelength intensities into the perceptual colormaking attributes by means of a mathematical model (http://www.handprint.com/HP/WCL/color7.html#CIECAM) of color vision.



comparison of
colorfulness and chroma

(right) we perceive the "same" orange color when we take into account any differences in illumination
(= chroma or saturation);

(left) seen as an isolated color, the black content of the orange has changed (= colorfulness)

By definition, *conceptual* colors are not perceived, so they do not in themselves have perceptual attributes. But the colormaking attributes can be appropriated to the logical or verbal definition of a conceptual color as is done, for example, with the theoretical definition of .

Three Material Color Components. Watercolor painters, as a tribe, are fond of saying that "primary" colors cannot mix the entire range of visual colors because all colors of paint or ink are *impure*. But as explained here (http://www.handprint.com/HP/WCL/color18a.html#cterror07) in more detail, the limited mixing range of material colorants has to do with the behavior of light as it interacts with color materials, not with their "impurity".

All *material* colors comprise three different components of light:

scattering (**W**). When light strikes any object, some portion of it does not affect any change in the material itself. The light is simply reflected back into the environment from the surface boundary between the material and the air, in random directions that depend on microscopic variations in the surface. This is *surface scattering* of light, and it adds *whiteness* to the visual color of the material.

chromatic reflectance (**C**). A substantial portion of the incident light passes through the surface boundary and throws its energy into the molecules that compose the material. This elevates the electron energies within the molecules. These disrupted electrons promptly emit the light again at specific wavelength energies that will return them to their original energy state; these discrete wavelengths aggregate into the material's unique *chromatic reflectance*. Some materials produce greater chromatic reflectance than others, producing an increase in the apparent chroma or saturation of the color. And many synthetic red, orange and yellow pigments produce chromatic reflectance that is very close to the hue purity.

infrared reflectance (**K**). The remainder of the light energy absorbed by the material is emitted by the electrons at much longer wavelengths, as heat. Some of this heat is held in the material, the rest is radiated back into the environment. However heat is invisible to the human eye a proportion of light goes into the material, but nothing visible comes out so the radiated heat adds a component of *blackness* to the visual color.

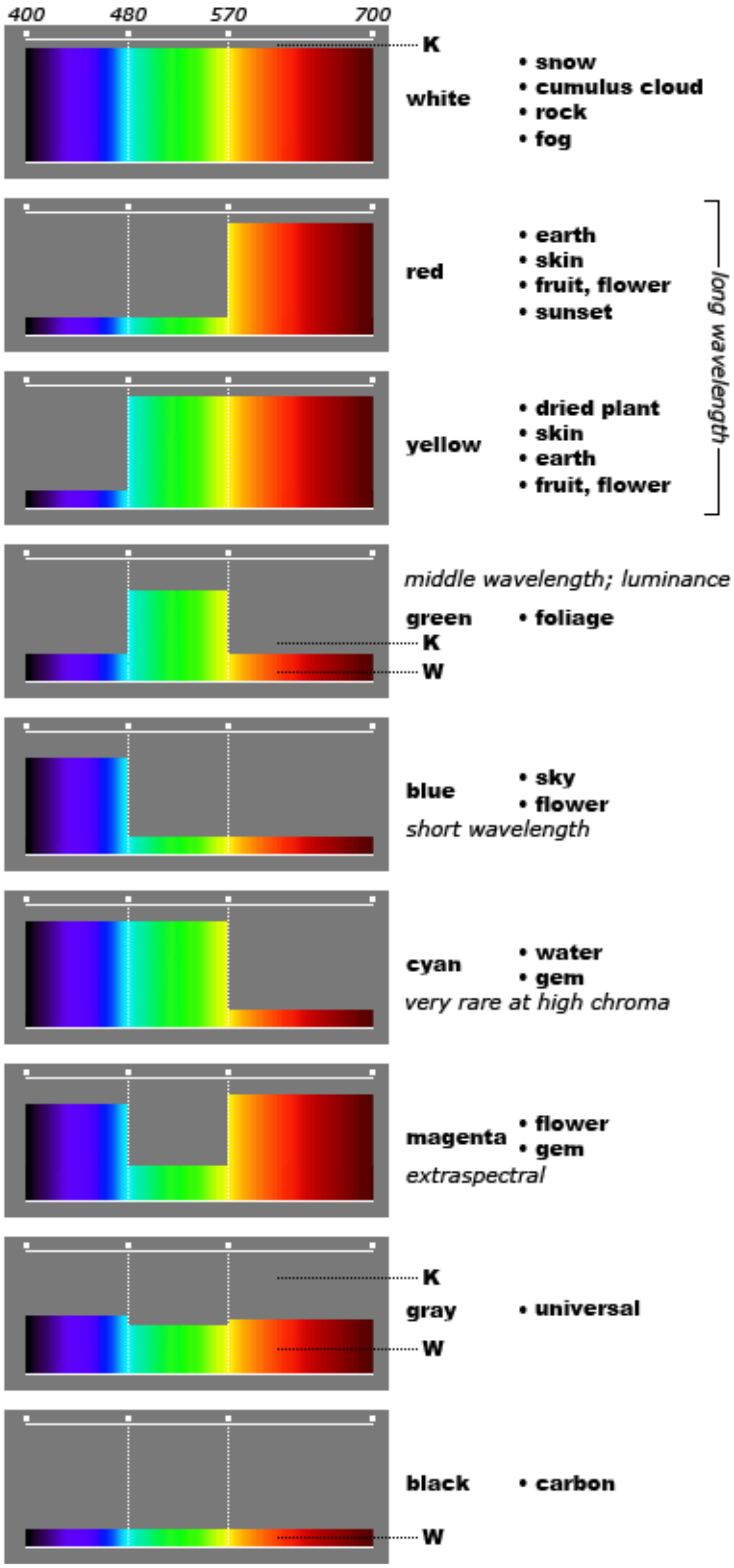
This is the accurate statement of the "impurity" in material colors:

All visual colors produced by light reflected from materials comprise a proportion of whiteness (W) caused by surface scattering, a proportion of pure chromatic reflectance (C), and a proportion of blackness (K) caused by the transformation of light into heat:

visual color = W + C + K

This formulation is too sweeping, as there are many materials that produce color by other means, such as refraction (spreading out the spectrum colors like a prism), iridescence (enhancing or canceling certain wavelengths through reflections from separate layers) and structural color. These color mechanisms are rare in the natural environment and nonexistent in artists' materials.

Categories of Material Color. Using a mathematical synthesis of surface colors (http://www.handprint.com/HP/WCL/color19.html), I demonstrate that the reflectance profile of any material can be divided into three reflectance sections at the wavelengths 480 nm and 570 nm (the monochromatic hues *cyan* and *yellow*), within arbitrary spectrum limits (e.g., 400 nm to 700 nm). Using these spectrum boundaries, all possible reflectance profiles can be categorized into one of nine *primitive color categories* based on the combined reflectance within each of the three spectrum segments (diagram, below).



the nine primitive color categories

Note that the minimum reflectance that is greater than 0% is usually due to white scattering (**W**), and the maximum reflectance that is less than 100% is due to infrared absorptance (**K**), as .

The reflectance categories *white, black, red, yellow, green* and *blue* are natural language color terms in most human communities, because these colors are very common in natural or manufactured objects. The terms *cyan* (blue green or green blue) and *magenta* (red violet) are nonexistent in almost all natural language lexicons, because these colors are extremely rare in natural and manufactured objects. Nevertheless, a systematic classification of reflectance profiles requires that they be included.

The *long wavelength* reflectance categories **red** and **yellow** are extremely common in natural materials (in particular iron oxides), define the color of all racial skin pigmentations, and are produced by incandescent materials (fire) and late day sunlight. The adjacent invisible spectral band is *infrared,* which corresponds to heat.

The *middle wavelength* reflectance category **green** is characteristic of nearly all plants, which appear as relatively dark colors because they absorb large quantities of light; however freshly sprouted plants often appear light valued and close to yellow. The spectral sensitivity that defines our luminance perception (http://www.handprint.com/HP/WCL/color1.html#newpsf) is most sensitive in the middle wavelengths.

The *short wavelength* reflectance category **blue** is characteristic of the color of the clear daylight sky and some forms of water; it is otherwise rare in natural materials, with the exception of flowers. The adjacent invisible spectral band is *ultraviolet,* which is almost completely filtered by the atmosphere, water and the cornea of the eye.

The mixed category **cyan** is extremely rare at high chroma, except in certain gems (tourmaline); no language identifies this color with a basic color term. At low chroma it is a common ocean color but is identified with a compound color name ("sea green").

The mixed category **magenta** (kin to *violet*) is also extremely rare in natural or artifical materials, except in certain flowers and gems; only technologically advanced languages identify it as a basic color term. It is an *extraspectral hue* that do not appear in a refraction or diffraction spectrum.

The achromatic colors **white** and **black**, and their mixture **gray**, are also extremely common in natural or artifical materials, are labeled in all language communities with basic color terms (sometimes as "light" and "dark"), and contribute to modify (whiten or blacken) the colors in every other category.

Light in Space. The most important perceptual fact of light is that it occurs *in three dimensional space*. As a preliminary to understanding color we must, very briefly, lay out some basic facts of light in space.

Illuminance & Luminance. All the material objects around us are made visible by the *quantity or intensity* of light that is shining on them. This quantity is called *illuminance:* it is the fundamental metric of lighting design for architects and interior designers, and it is measured in specific units (http://www.handprint.com/HP/WCL/color3.html#illuminance) (*lux* or *foot candles*). It is a physical fact of the visible environment around us.

Surprisingly, illuminance is invisible! If we are surrounded by empty space, with our back turned to the light source, all we can see is darkness. We actually only see illuminance either by looking directly at the light source, which appears as *emitted light*, or by looking at surfaces around us, which display *reflected light*. These two subjective qualities of light are called *brightness* and *lightness* respectively and I'll explain in a moment what those terms really mean.

Now, we can only see these emitted or reflected light sources as objects in space that have a certain visual size (visual width and breadth). So the light that we actually perceive is the emitted or reflected light in relation to the visual area that produces the light. This *area dependent quantity* of light we can see because it is emitted or reflected by a source of a specific visual size is called *luminance*. This is the fundamental metric of photographers and video engineers, and it is also measured in specific units (http://www.handprint.com/HP/WCL /color3.html#luminance) (*candelas per square meter,* abbreviated *cd/m*^{2}, or the more arcane *foot lamberts*).

Luminance Adaptation. The luminance of light reflected from surfaces to our eyes has an enormous environmental range (http://www.handprint.com /HP/WCL/color4.html#sensitivity) from a white surface under a starry sky (0.0003 cd/m^2) to a white surface under noon sunlight (30,000 cd/m^2 or more). This is a difference in light intensities of 100 million to 1.

For purely physical reasons, no animal visual system (nor any video or photographic system) can encompass an energy range that large by a single response process. Instead, the human visual system can perceive at any time a luminance range of about 100,000 to 1, or 0.1% of the environmental range! To compensate for the missing 99.9%, the relative sensitivity of our eyes is increased or decreased by a process of **luminance adaptation**, which includes the familiar changes in pupil size but also requires changes in the light sensitivity of the retina and in the nerve pathways into and within the brain.

These changes produce very familiar and distinct changes in the appearance of colors. Most of these changes can be handily summarized as four *luminance* *regimes,* which produce four distinct levels of luminance adaptation: *scotopic* or night vision, *low mesopic, high mesopic* and *photopic* or noon daylight vision (table, below).

four levels of luminance adaptation

adaptation level	*ambient light level*		*color experience*
	illuminance	*luminance*	
scotopic	less than 1 lux	less than 0.3 cd/m^2	poor contrast achromatic no detail
low mesopic	1 to 100 lux	0.3 to 30 cd/m^2	low contrast muted color coarse detail
high mesopic	100 to 1000 lux	30 to 300 cd/m^2	good contrast good color good detail
photopic	more than 1000 lux	more than 300 cd/m^2	bright color high contrast fine detail

As this table shows, luminance adaptation affects three fundamental dimensions of our color experience: (1) the perceived amount of *contrast* between white and black, (2) the perceived amount of *hue purity* or intensity of colors (amount of contrast between an intense color and a matching gray), and (3) the amount of *detail* perceptible in objects, images, textiles, textures and text.

Our visual response through all gradations of artificial light, and of natural light dimmer than full noon sunlight, is a mixture of both rods and cones, and therefore constitutes *mesopic vision*. Photopic vision is the experience of outdoor summer noon sunlight, and the intense artificial illumination of a surgical theater.

We are normally unaware of (or ignore) the small color changes within high mesopic to photopic vision that occur in transitions across different natural or artificial illuminance environments. However, the transition from low mesopic to scotopic vision, which occurs in the hour after a cloudless sunset (http://www.handprint.com/HP/WCL/color4.html#lumcolors), produces strong and recognizable changes in color appearance (image, right). At first and briefly, reds become more luminous, as the **M** and **S** cones lose sensitivity relative to the **R** cone; then the **R** cone also becomes less senstive, and all colors decline into impoverished warm/cool contrasts (tans and browns, vs. greens and blues), and finally into shades of gray approximately one hour after sunset; parallel with these color transitions, whites decline into a luminous gray.

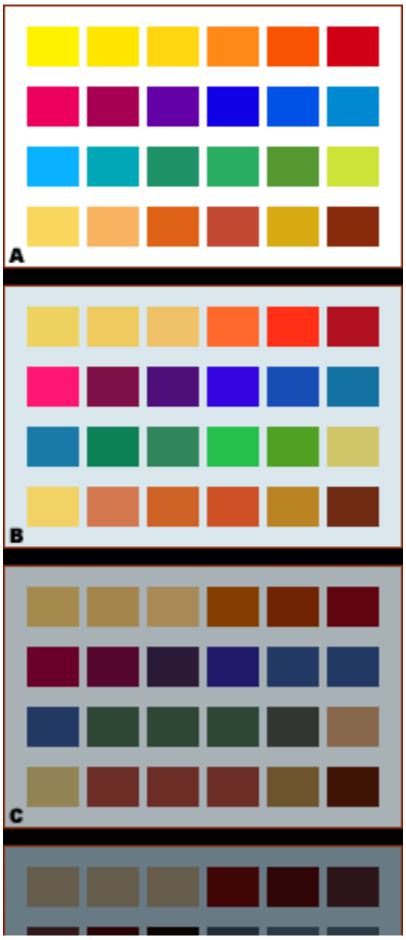
In our homes and offices we have window blinds, and outdoors use sunglasses, to moderate light from the sun; and we use interior lighting to remedy enveloping night or a lack of windows. These adjustments clearly indicate that our preferred light regime is in the high mesopic. Your computer screen, for example, produces the "white" of this web page with a luminance of around 100 cd/m^2, and the page of a book under good reading light is at least 70 cd/m^2, while the luminance preferred for detail tasks in hospitals or factories is up to 300 cd/m^2.

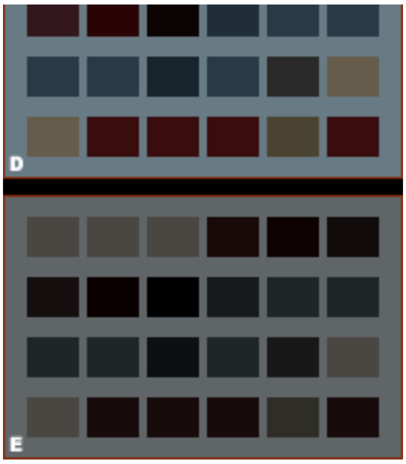
I will return to luminance levels and luminance adaptation in considerations of color design. For now, the two essential points are (1) the strong interconnection between the *illuminance* or light level, the *luminance* or reflected light of surrounding surfaces, and the *luminance adaptation* of the eye to the surrounding luminances; and (2) the qualitatively distinct changes in color experience produced by changes in these three factors.

The Illuminant. We have sufficiently anchored our perception of illuminance and luminance within three dimensional space and a specific adaptation level. Light still has two other qualities, and both have to do with color.

When we think of the color of objects, we naturally think of them under a specific type of light *white light* or light that is "colorless". The reason for this assumption is that the apparent color of reflecting surfaces is always the *subtractive mixture of surface color and light color*. In effect, light mixes with surfaces in the same way that paints mix with each other. And if we wanted to judge the hue of a yellow or red paint, we obviously would not do so by mixing it with a green or blue paint! Instead, we would mix it with white paint.

Now, it seems reasonable to define a "white" light as a light source that emits every wavelength of light in equal proportion. As it happens, however, by the standard of "equal wavelengths", *no natural or artificial light is perfectly colorless!* Instead, lights have some color bias (http://www.handprint.com/HP/WCL/color1.html#solarlight), which can be approximated by the mixture of a perfect white light with a colored light. The proportion of colored light (http://www.handprint.com/HP/WCL/color3.html#purechroma) in the mixture defines the *chromaticity* (combined hue and hue purity) of the light.





color changes from low mesopic to scotopic vision

A: color appearance in daylight at sunset; **B-E**: color changes in 15 minute increments after sunset

However, a more indirect definition than chromaticity has proven useful. For purely physical reasons, the chromaticity variations in natural and artificial "white" lights correspond closely to the apparent color of a heated metal or, more precisely, to the color of a theoretical, perfectly nonreflecting heated object called a blackbody (http://www.handprint.com/HP/WCL/color12.html#blackbody).

If we generate a **blackbody spectrum** in increments on the Kelvin (absolute) temperature scale from 1000°K up to 100,000°K or more, we reproduce colors only across a single chromaticity path starting at orange red, through orange into yellow, from yellow into white and ending in pale violet blue. This curving chromaticity line is called the **blackbody locus** (diagram, right). (As we increase the blackbody temperature, the *luminance* of the material increases enormously, but we disregard luminance when thinking about chromaticity.)

Then the chromaticity of all incandescent light sources can be characterized by the *correlated color temperature,* which is the theoretical temperature of the blackbody spectrum with the closest matching chromaticity (table, below).

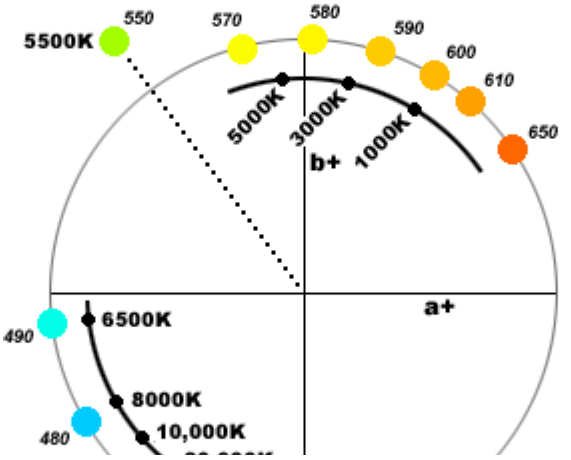
correlated color temperatures

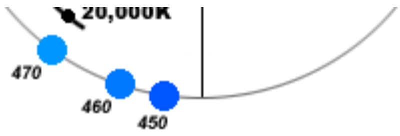
for common illuminants and light sources

rK° color correlated illuminant or light source 1000 lower limit of blackbody curve 1850 candle flame 2000 sunlight at sunrise/sunset (clear sky) 2750 60W incandescent tungsten light bulb 2860 **CIE A**: 120W incandescent light bulb 3400 photoflood or reflector flood lamp 3500 direct sunlight one hour after sunrise 4100 **CIE F11**: triband fluorescent light 4300 morning or afternoon direct sunlight 5000 white flame carbon arc lamp 5003 **CIE D50**: warm daylight illuminant 5400 noon summer sunlight 6400 xenon arc lamp 6500 average summer daylight 6504 **CIE D65**: cool daylight illuminant 7100 light summer shade 7500 indirect northern skylight 8000 deep summer shade 9300 "white" of a computer monitor 10640 clear blue sky **Sources**: Mitchell Charity, MIT; Kodak USA

Note: Color samples grossly exaggerate the chromatic contrast and drastically reduce relative luminance for purposes of visual illustration.

The diagram (below) presents the blackbody chromaticities as locations around the hue circle. This shows that shifts in natural light correspond quite well with the traditionally defined warm/cool contrast (http://www.handprint.com /HP/WCL/color12.html#warmcircle).





color analogs to daylight spectra chromaticities

the hue of blackbody temperatures illustrated as spectral locations on the CIECAM a*b* plane (http://www.handprint.com/HP/WCL/color2.html#huespace); solar light has a CCT of about 5500°K

Keep in mind, the correlated color temperature is only useful to describe sunlight, daylight and incandescent forms of artificial light. Fluorescent lights can produce misleading results, and green or magenta Christmas tree lights would possibly have CCTs near white, which is nonsensical. Note also that these chromaticities depend on the brightness of the light: fluorescent "daylight" reading lights appear unpleasantly bluish because they are relatively dim, and a 30 watt incandescent bulb may appear distinctly yellow while a 200 watt bulb will appear white.

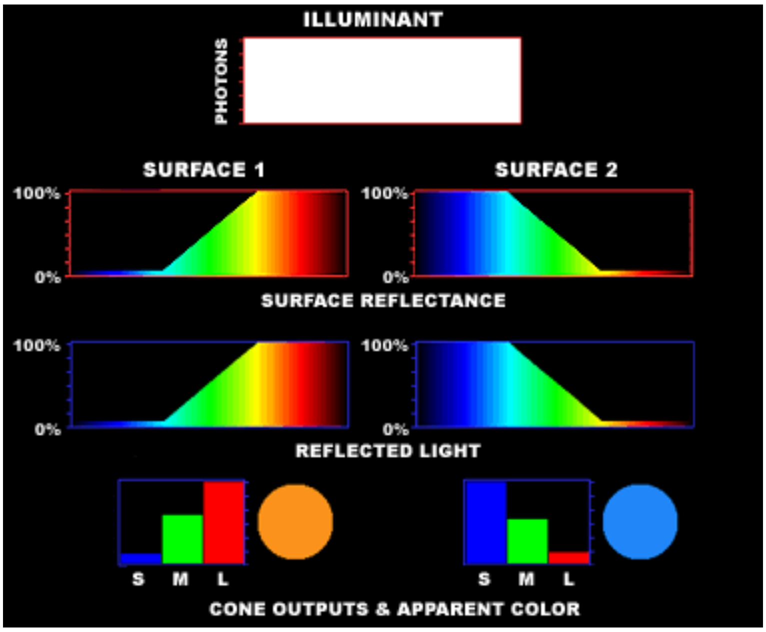
The CCT is primarily a way to determine the chromaticity balance between yellow/red and blue, which photographers and painters use to determine the color bias of light from reflected surfaces, as this affects the adaptation of the eye, film emulsions and the apparent color of objects. This contrast is so basic that it has a simple description: CCTs lower than 6500 are termed **warm**, and CCTs above 6500 are termed **cool**.

Because humans evolved in outdoor environments, we are adapted to see factually bluish daylight as "pure white" light, and the **D65** illuminant is used as the daylight standard of comparison for artificial lights. Most incandescent lights produce a light that is quite yellow, where the **A** illuminant is a reasonable match.

This highlights an important paradox in the relationship between luminance levels and color experience: as illuminance increases, surfaces appear more chromatic, but lights close to the blackbody locus appear less chromatic (closer to pure white).

The Illuminant & Material Colors. The significance of the illuminant in color experience is that **material colors mix subtractively with the light that illuminates them**. We normally assume that the appearance of a surface color is the "real" or "true" color of the surface, because our eye has adapted to accept the prevailing illuminant as "white" light. But this obscures the consistent rule that any surface color we see is actually the *subtractive mixture* of the material and illuminant colors.

The image (below) sets up the ideal situation: a "white" illuminant, containing all wavelengths in equal proportions, illuminates surfaces that reflect either some "green" and all "red" light (left), or some "green" and all "blue" light (right), producing the visual experience of an orange or blue color. These are in fact complementary colors, as nearly opposite in hue as color vision allows.

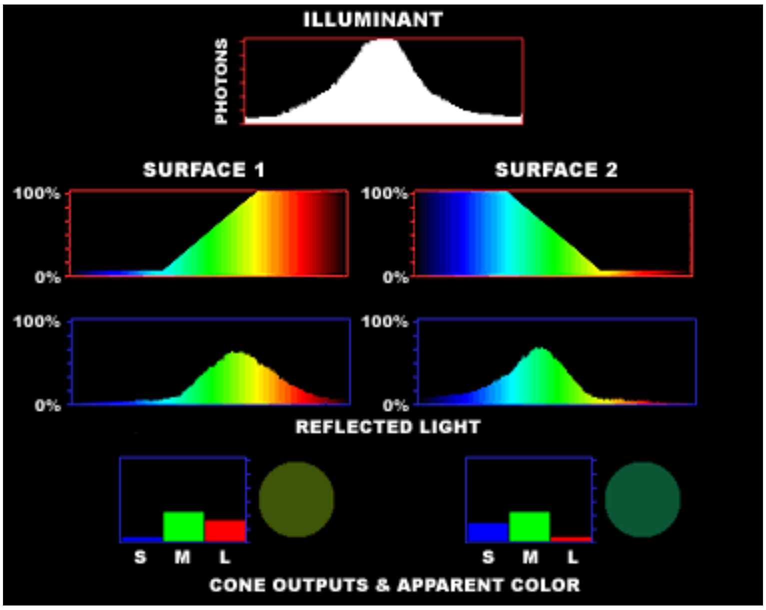


the subtractive mixture of light and surface color

the product of a single illuminant on two complementary colored surfaces;

adapted from Jeff Beall, Adam Doppelt & John Hughes © 1995 Brown University

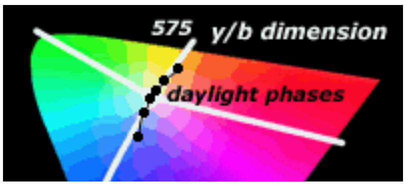
However, if we now illuminate these two contrasting material colors with a "green" illuminant containing light mostly in the middle wavelengths, the effect on the visual colors is quite pronounced (image, below).



restricted light emission and metamerism

the product of a single illuminant on two complementary colored surfaces; adapted from Jeff Beall, Adam Doppelt & John Hughes © 1995 Brown University

In the orange surface, the "red" reflectance is suppressed because there is little "red" light in the illumination, and the "blue" is suppressed by the surface absorptance. As a result, only the "green" wavelengths are reflected. The same effects apply, in complementary fashion, to the blue surface, so that again only "green" wavelengths are reflected. As a result, the orange and blue appear to be two similar shades of dull green.



the blackbody locus in the CIELUV chromaticity plane

If we consider the illuminant color as acting in the same way as a tinted filter placed between the reflecting surface and the eye, then we can deduce a few consistent principles as to how this subtractive mixture of light and material color affects hues around the hue circle (images, right):

The chromaticity of the light defines a location on the hue circle, and all visual color shifts are in relation to this point.

Material colors analogous to the illuminant hue become lighter valued and more saturated.

Material colors complementary to the illuminant hue become darker and desaturated; under strongly tinted light they may appear achromatic (gray).

Material colors quadratic on either side of the illuminant hue shift toward the illuminant hue and become somewhat less saturated.

The photographs below, using a camera that did not compensate for the illuminant chromaticity, show the effects of different hues of light on a material hue circle. To illustrate these effects, I've photographed a color circle consisting of the standard 18 hues (http://www.handprint.com/HP/WCL/color18a.html#huecategories) in watercolor paints, illuminated by six different types of light. This procedure was not carefully controlled, but it illustrates the types of visual color changes that we encounter in materials under different types of light (image, below).

illuminant and color rendering

a color circle of 18 watercolor paints, plus black, viewed under daylight (equivalent to standard illuminant **D65**), incandescent light (**A**), and red (**R**), yellow (**Y**), green (**G**) and blue (**B**) spot lamps; *mouseover* to view colors against a neutral gray background

The differences among the corresponding colors are easier to see if we extract the color samples from the "white" background and display them against a neutral background (mouseover, image above).

This subtractive mixing of surface and light source also produces a fundamental color ambiguity: it is possible and commonly happens that (1) two different material colors (reflectance curves) can produce the same apparent color under the same illuminant, including nominally "white" light, and (2) materials that are visually identical under one kind of illumination will appear different under another kind of illumination, even if both light sources appear to provide "white" illumination. These are situations of *metamerism,* and the visual colors that appear different under some illuminants but the same under other illumiants are called **metameric colors**.

Metameric colors are commonly grays and dull (unsaturated) hues; extremely impoverised or monochromatic illuminants are generally required to produce metamerisms among highly saturated material colors, and typically because all material colors then appear to be bright or dark variations on a single hue.

Color Rendering. Metamerisms introduce us to a third quality of light, perhaps the more subtle. The *color rendering* quality of a light is simply the appearance of a complete range of colors as illuminated by the light, in comparison to the appearance of the same colors under natural daylight at the same illuminance.

simulation of corresponding colors

(top) nuance color circle; (middle) nuance color circle under orange illuminant; (bottom) corresponding colors under white illuminant

Daylight and direct sunlight have perfect color rendering properties both because they are broadband (all wavelengths are present) and because our visual system, eyes and brain, have evolved to accept daylight as "pure white", despite the fact that it is, objectively judged, somewhat bluish.

However, sunlight under other circumstances seen through clouds of smoke, or low on the horizon and natural lights that are either strongly biased, or entirely missing some wavelengths from their spectrum, cause significant changes in the appearance of colors, and these push white point beyond the chromatic adaptation capability of our visual system.

Daylight and all forms of *incandescent* (produced by physical heat) artificial light at high mesopic levels of illuminance produce perfect color rendering. Many forms of *fluorescent* (produced by electrical discharge) lights have poor color rendering, even when they appear to be "white" lights. This is because fluorescent lights have very uneven or "gappy" emittance profiles, so that surfaces that reflect wavelengths corresponding to these gaps will appear unnaturally dark or dull, and surfaces that reflect light that corresponds to the peaks will appear unnaturally bright. (Most supermarkets utilize special fluorescent lights to make their garden produce appear especially fresh and green.)

Viewing Geometry. A final point is that visual color can depend on the spatial relationship between a surface, a light source and the eye, which is called the *viewing geometry*. This is defined by two completely independent quantities:

the **illumination geometry**, measured as the angle of incidence between the light source and the surface; and

the **receptor geometry**, measured as the angle between the surface and the line of sight to the eye, camera or photometer.

These are usually notated as degrees from the perpendicular, separated by a slash: **0/45** indicates that light falls perpendicularly onto the surface, and the surface is viewed from a 45° angle at one side. Diffuse illumination, which arrives at the surface from all directions, is indicated by a lowercase **d**, as in: **d/45**.

The intent of this digression is simply to make you aware that color can change signficantly due to the viewing geometry. We are all familiar with the fact that glossy or highly reflective surfaces produce a strong glare wherever the illumination and receptor geometries are equal and spatially opposite. But surfaces also generally appear whiter and more reflective (contain a larger proportion of scattered white light) if viewed from a very oblique angle (such as **d/80**). And both pearlescent and iridescent colors change significantly at viewing geometry changes, either by moving the light source or by changing continuously the receptor geometry (e.g., moving the head back and forth).

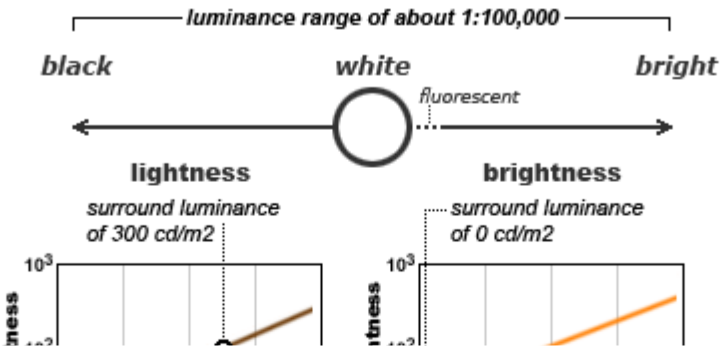
Light Summary. Our visual experience is defined by the objective, physical quality of light in the environment. This quality comprises three basic components: (1) the *light level* that is created by *illuminance,* which produces a corresponding *luminance* from reflecting surfaces and *luminance adaptation* in the eye, (2) the *illuminant* or *correlated color temperature,* which defines the chromaticity (hue and hue purity) of the illuminance, and (3) the *color rendering,* which measures the difference between colors as they appear under the dominant light source and under daylight. Viewing geometry, or the relative angles of light incidence onto a surface and light reflection to the eye, may also signficantly affect color appearance, especially in glossy or highly polished surfaces, at extremely oblique angles, and in iridescent or pearlescent materials.

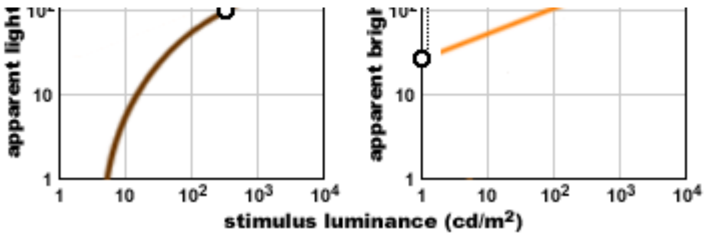
Brightness & Lightness. We have separate terms for the quality of light that seems to be emitted by a light source (*brightness*) or reflected by a material surface (*lightness*). But if both are just forms of luminance, why do they appear to us so different?

The answer is: the luminance is always perceived *within a spatial context,* which is just "everything that visually surrounds" the luminance in the two dimensional space of an image (on both sides, above and below) and in the three dimensional space (in front and behind) that we interpret from the image. These separate interpretations define the two basic components of color context: *contrast* and *spatial interpretation*.

Luminance & Contrast. Considered only in terms of luminance contrast, *brightness* is luminance perceived in a context of *relative brightness,* and *lightness* is luminance perceived as a quality of *relative blackness*.

The pivot point between these black and bright visual experiences, and the conceptual center of our luminance adaptation, is the color sensation *white,* the color that contains neither blackness nor brightness. Everything with luminance below white is perceived as having an increasing quality of *black*, and luminances above white are perceived as having an increasing quality of *bright*.

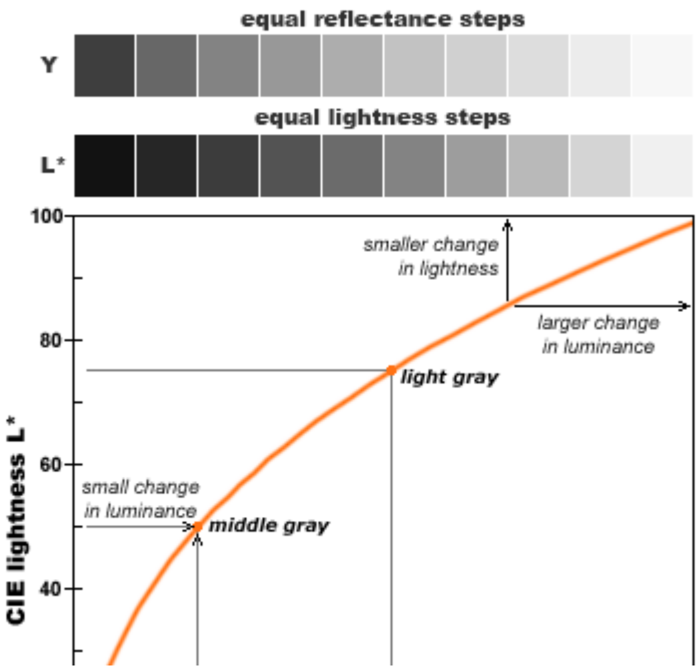


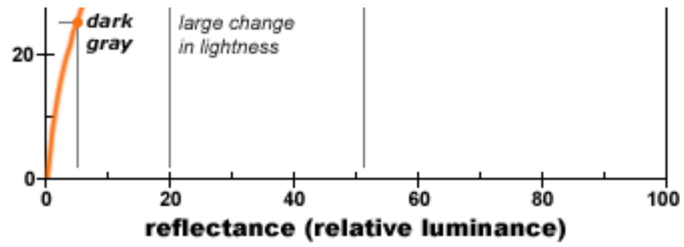


comparison of lightness and brightness

The diagram (above) summarizes this contrast as a scale and two graphs. The scale shows white as the balance point between **bright** and **black**, with the ambiguous area termed *fluorescent*, which can be described as light that is too faint to cast a nearby shadow.

The two graphs show the key difference between lightness (a diffuse light perceived against a "white" background at 300 cd/m^2), which forms a curve, and brightness (a diffuse light perceived against a completely dark background), which increases steadily as luminance increases. The lightness curve indicates that there is greater visual sensitivity to small changes in luminance in blacker (darker) values (the curve is steeper), and that lightness sensitivity extends down to a luminance that is about two orders of magnitude (10^2 or 1/100th) less than the luminance of white.





reflectance (relative luminance) and lightness

The diagram (above) expands on these points. The color that we perceive as a "middle" gray has only about 20% of the luminance (reflectance) of a pure white. If we create a 10 interval grayscale of equal 10% increases in reflectance, then the third step in the scale is a middle gray. In contrast, if we create a 10 interval scale of equal 10% increases in lightness, most of the steps appear relatively dark valued. This corresponds to the fact that, at low luminance values, small changes in luminance produce large changes in lightness, and at higher luminance values, a much larger increase in luminance is necessary to produce an equivalent perceptual change in lightness.

Both brightness and lightness are *contrast perceptions:* they define the luminous quality of a color in relation to some benchmark or standard.

Luminance & Spatial Interpretation. Because lightness is inherently a *contrast* perception, different types of spatial contrast can produce different visual colors.

The case of two dimensional color contrasts was explored systematically in the 19th century by , and the theory of simultaneous color contrast (http://www.handprint.com/HP/WCL/chevreul.html) is well known to every artist:

"In the case where the eye sees at the same time two contiguous colors, they will appear as dissimilar as possible, both in their optical composition [hue] *and in the height of*

their tone [mixture with white or black]."

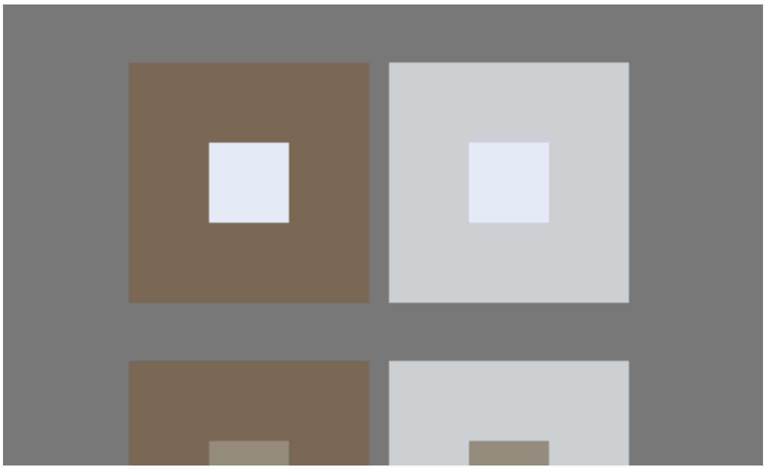
These visual color changes are commonly illustrated with a "square within a square" diagram, as for example in the contrast of a dull middle blue surrounded by a similarly dull dark or light blue:

color shift in a simultaneous lightness contrast

all large and small squares have the same hue and chroma

Here the central squares are exactly the same material color (i.e., computer monitor color), but the visual color appears darker when joined with the lighter surround (on the right), and lighter when joined with the darker surround (on the left). (Focusing your gaze on the central black dot will make this contrast more obvious.)

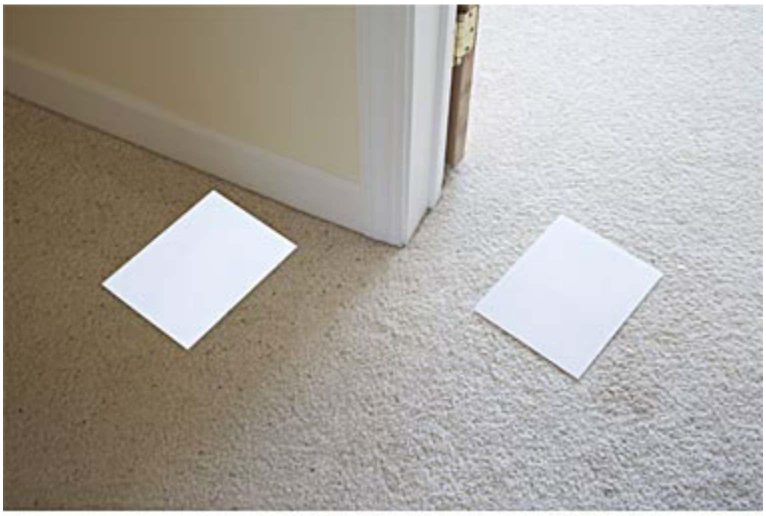
Here is another example, using a light valued or middle valued central square and contrasting light and dark surrounds. In both cases, the surround pushes the central color in the opposite direction, enhancing the visual contrast.

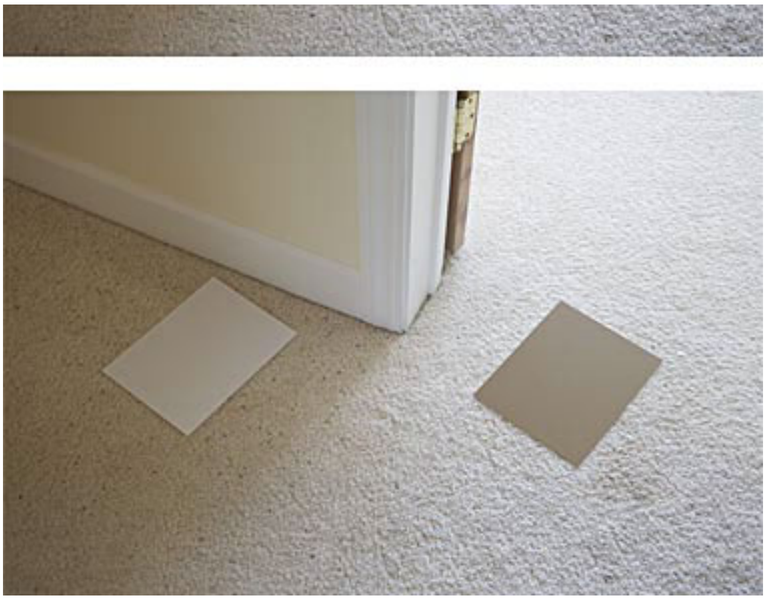


planar simultaneous color contrast

central squares are lightness **L*** = 93 (top) and **L*** = 59 (bottom); surrounding colors are **L*** = 45 (left) and **L*** = 83 (right)

These color shifts may appear rather small. However, the images below show two identical sheets of white paper, one lying in shadow and the other in diffuse daylight. One photo shows the actual appearance; the other two photos show what happens when the color of the shadowed or illuminated paper is copied into both sheets.





spatial simultaneous color contrast

a sheet of white paper viewed in shadow (left) and diffuse daylight (right) *(middle row)* the original photograph; *(top row)* illuminated paper color copied into shadowed paper outline; *(bottom row)* shadowed paper color copied into illuminated paper outline

The lightness differences between the central and surround colors in the two dimensional display (previous figure) excluded any effect from illumination. But the three dimensional display requires us to interpret the color area contrasts as consistent with objects illuminated by light in space. And the only way to produce a consistent *spatial perception* is through a radical change in the *visual color*. Two effects appear:

increased contrast - the comparative impact of the color differences is greater: we perceive a much greater difference between the illuminated and shadowed surfaces than in the simultaneous contrast demonstration. You may even see the "light" colored paper in shadow (image, top left) as *brighter* than the nearby white background of this web page.

decrement is greater than increment - copying the shadowed area into diffuse light produces a color darkening that appears greater than the lightening that appears when the lighted area is copied into shadow: the same luminance discrepancy has a much greater "blackness" (decrement) than "brightness" (increment) visual impact. And this is consistent with the of lightness perception: if we take any point on the curve as the starting luminance value, a decrease in the luminance will produce a greater lightness change than will an increase in luminance by the same amount.

The remarkable visual differences between two dimensional and three dimensional displays of the same color contrasts signify that color is not the *quality of light* reflected from materials, but the *interpretation of light* within a three dimensional space.

We end our exploration of luminance effects in color vision by returning to the definition of color we started with. *Color is a context judgment of surfaces viewed under light in space* even when the objects in space appear as a two dimensional image.

Hues Within the Opponent Dimensions. Issac Newton (http://www.handprint.com/HP/WCL/color2.html#huecircle) was the originator of the **hue circle**, the organization of all hues as a circumference in which neighbor hues correspond to neighbor wavelengths of light in the spectrum and are judged to be perceptually similar colors.

Exactly *how* neighbor hues are spaced in the hue circle has been an evolving standard. Newton organized his hue circle according to the apparent lengthwise spacing of hues in a prismatic spectrum (which expands the spacing of "blue" and "blue violet" wavelengths relative to the "orange red" wavelengths), and, to complete the circumference, determined the spacing between his "red" and "violet" wavelengths according to an arbitrary standard (diatonic).

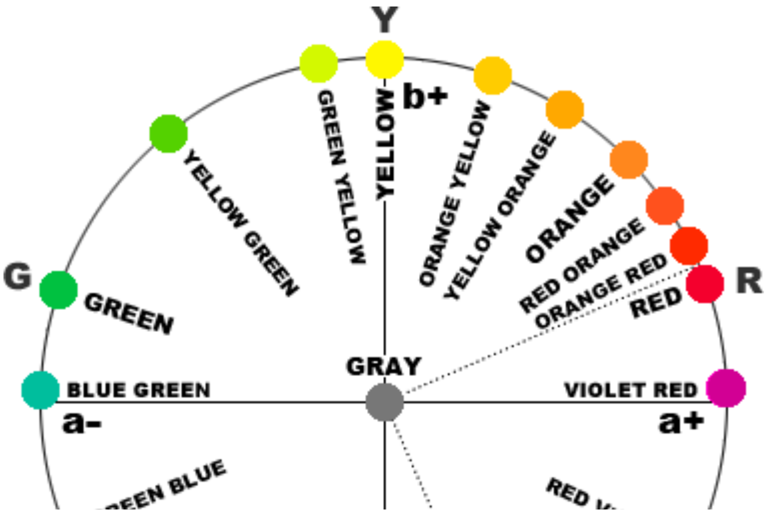
Adapting Newton's scheme, 18th century artists (http://www.handprint.com/HP/WCL/color6.html#materialtrichromacy) developed the concept of partitioning the circumference into equal thirds, anchoring each division on a subtractive "primary" color (red, yellow or blue), then deriving the spacing of hues between each pair of primaries according to the relative proportions of the two primaries required to mix them. *Secondary colors* were for example colors mixed from equal proportions of two primaries, which placed each secondary color directly opposite the third primary on the hue circle. As all three subtractive primaries (http://www.handprint.com/HP/WCL/color5.html#theorysub) were asserted to make a "pure black" when mixed in equal proportions, the secondary colors confirmed the hue circle relationship of **complementary colors** also suggested by Newton (http://www.handprint.com/HP/WCL/color2.html#mixingcircle): paint or ink mixtures opposite each other on the hue circle would always mix a neutral color.

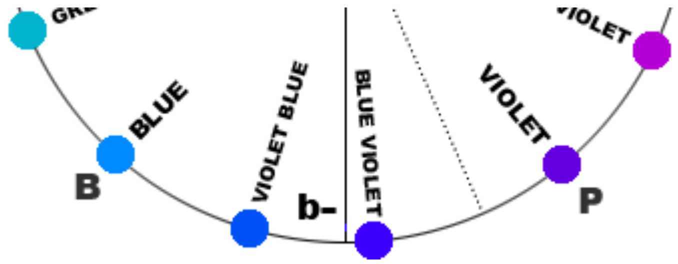
Eventually 19th century color scientists (http://www.handprint.com/HP/WCL/color6.html#trichromatic), using more sophisticated light measurement tools, established the perceived spacing among spectral hues as additive mixtures (http://www.handprint.com/HP/WCL/color5.html#theoryadd) of three "primary" lights in a chromaticity diagram (http://www.handprint.com/HP/WCL/color6.html#CIE1964). This provided the basis for the development of colorimetry (http://www.handprint.com/HP/WCL/color6.html#colorimetry) the measurement of *visual color* as the measurement of *material color* in emitted or reflected light.

Further study showed that neither the additive mixture of primary lights nor the subtractive mixture of primary paints could directly reproduce the *perceptual* spacing between hues around the hue circle the apparent similarity or difference between colors judged purely by eye. This led to extended research into the perceptual spacing of colors, first as the comprehensive inventory of equally spaced color exemplars in the Munsell Color System (http://www.handprint.com

/HP/WCL/color7.html#MUNSELL) (1929); then as complex mathematical models that attempted to reproduce the perceived color spacing entirely from the measured material color, as in the CIE uniform color space (http://www.handprint.com/HP/WCL/color7.html#CIELUV) (1964) or the OSA uniform color scales (http://www.handprint.com/HP/WCL/IMG/OSA /index.html) (1974); and finally as fully developed color appearance models, such as CIECAM (http://www.handprint.com/HP/WCL/color7.html#CIECAM) (2002), that take into account the effects of other factors (color luminance, contrast, surround colors, spatial size and luminance adaptation) on color perception.

All perceptual color models developed since the middle 20th century are based on opponent dimensions (http://www.handprint.com/HP/WCL /color2.html#opponentfunctions) that account for both the hue and chroma of all colors at equal luminance. First proposed as a scientific theory in the early 20th century (by Ewald Hering (http://www.handprint.com/HP/WCL /color2.html#heringtheory)), this modern framework is based on the conceptual opponent contrast between VIOLET RED vs. BLUE GREEN (defining the **a**+/**a** dimension) and YELLOW vs. BLUE VIOLET (defining the **b**+/**b** dimension). All hues can be organized around this opponent hue circle so that the circumferential distance proportionately the perceptual difference, and *visual* complementary colors are opposite each other (diagram, below).





the opponent dimensions and hue categories

the y/b and r/g opponent dimensions and central hue locations on the CIECAM hue plane at lightness 6; dotted lines indicate area of extraspectral hues (mixtures of "orange red" and "blue violet")

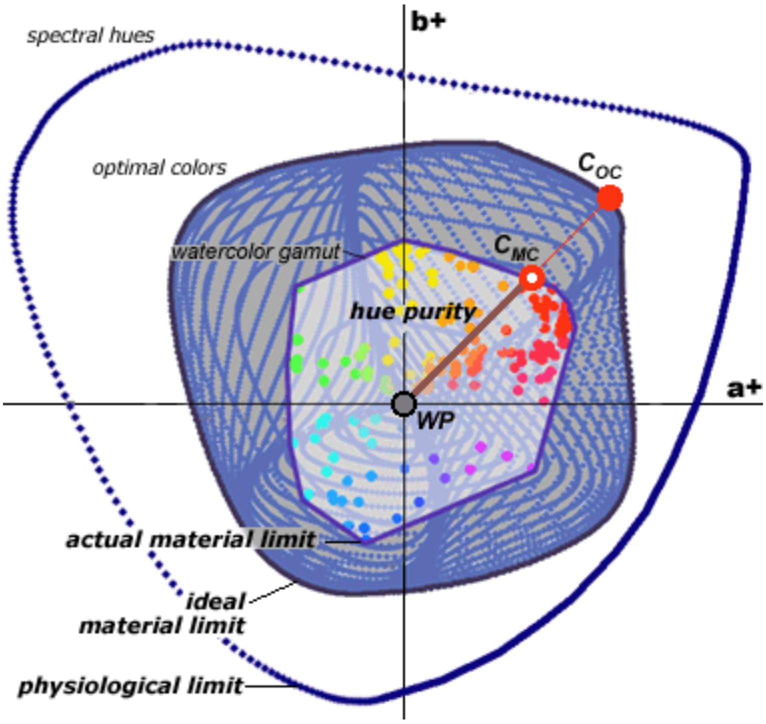
The use of capitals (such as GRAY) indicates that these are **concept colors** rather than visual or material colors, but the distribution of material colors within this space (for example, as shown here (http://www.handprint.com/HP/WCL/color7.html#CIECAMab)) is extremely good.

The accurate reproduction of *perceived* color relationships is the principal benefit of these opponent dimensions. The second benefit is that color relationships are entirely divorced from any "primary" color framework. This detaches color both from the litter of 18th and 19th century "color theory" based on the concept of "primary" colors (such as system critiqued above), and from any single material definition as paint mixtures or as light mixtures. The measurement of color is anchored in the fundamental habitat of color: the *perceiving mind*.

This also does away with the specious and imaginary hierarchy among hues as primary, secondary, tertiary, pure or impure, primitive or derived, which is the third benefit of the opponent dimensions. Hues are simply hues, and (as Newton observed (http://www.handprint.com/HP/WCL/color2.html#colormind)) all hues are equally "simple" or "homogeneal". This leads to a straightforward framework for labeling hues (http://www.handprint.com/HP/WCL/color18a.html#huecategories), based on the basic hue names (http://www.handprint.com/HP/WCL/color2.html#language) *red, orange, yellow, green, blue* and *violet* and the 12 paired compound names.

Three Chromaticity Spaces. The opponent dimensions allow us to map the relative appearance of many different types of material color, and this shows that visual color can be separated into three distinct color spaces, defined not by hue or by brightness/lightness, but by the **maximum hue purity** (chroma or saturation) any color can achieve.

These three domains are (1) the physiological limits of the retinal photoreceptors, produced by monochromatic lights or *spectral hues,* (2) the ideal limits of perfectly reflecting colored materials, defined as theoretical *optimal colors,* and (3) the actual limits of the most saturated pure pigments or dyes displayed in a transparent medium, or *media gamut*. The diagram (below) shows the relationship among these three color domains on the CIECAM (http://www.handprint.com/HP/WCL/color7.html#CIECAM) $\mathbf{a_C b_C}$ (chroma) plane.



three chromaticity spaces

visualized on the CIECAM $\mathbf{a_C b_C}$ chromaticity plane

The *physiological limit* in color appearance is traced by monochromatic lights or single wavelengths from the visible spectrum. Displayed at optimal contrast against a dark neutral background, no physical stimulus can produce a more saturated color appearance or a wider range in brightness. The definition of these physiological limits depends only on the trichromatic **L**, **M** and **S** outputs. The limits are partly constrained by the fact that a light stimulus projected onto the retina will always stimulate more than one type of cone, and this receptor "mixture" reduces the color saturation.

The *ideal material limit* of surface colors is identified through the mathematical fiction of optimal colors (http://www.handprint.com/HP/WCL/color3.html#optimalstimuli), which are ideal materials that either completely reflect or completely absorb all light at each wavelength. This produces ideal surface colors, in a complete lightness range from absolute black to luminous white, that are as saturated as possible in every hue across the full range of lightness. Their limits are established by the fact that the lightness of a material increases from pure black as the proportion of reflected wavelengths is increased, but these multiple reflected wavelengths are mixtures of single wavelengths that produce colors less saturated than single spectral lights. However, unlike actual material colors, these theoretical colors entirely exclude any whiteness from surface scattering, and have very sharply defined reflectance profiles.

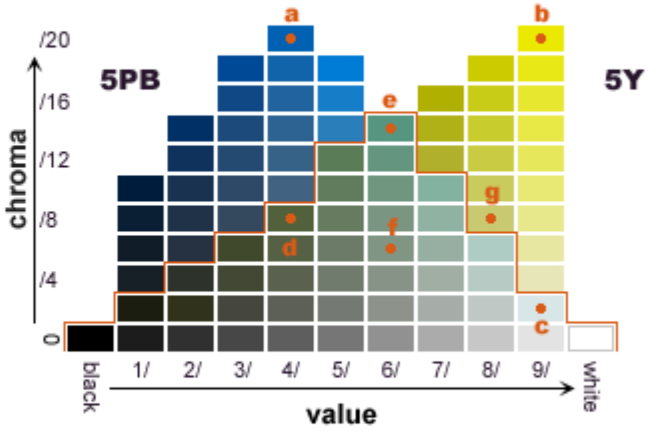
The *actual material limit* is determined by the interactions of matter with light. Because they never completely absorb or reflect all the light at each wavelength physical surfaces channel some luminance into invisible infrared wavelengths and scatter some as diffuse "white" light, producing rounded and darker reflectance profiles they are inherently duller than optimal colors of the same hue and lightness, and they have a more restricted lightness range. Material color has a characteristic quality of *grayness,* the combination of white scattering and black absorptance, even in a white color. This grayness is the difference between material and optimal color.

These three chromatic domains highlight the important and obscure relationship between *brightness/lightness* and *chroma*. Both depend on **relative luminance**. As explained above, the perception of both and depends on whether, and how, we take into account the effects of illumination and luminance contrast. This distinguishes them both from perceptions of hue, and positions both brightness/lightness and chroma as **symbols or signs of higher luminance**.

In fact, it is possible using luminance contrast alone (http://www.handprint.com /HP/WCL/color2.html#grayness) to make a surface color appear to glow or shine like a light, with a corresponding increase in its apparent chroma (images, right). Art galleries exploit this fact to make their paintings appear more luminous, vignetting them with faint spot lights that enhance luminance contrast with the subdued illumination of the gallery space.

The Nuance Space. Another indication of the relationship between luminance and chroma is that each hue can reach its maximum chroma only at a specific lightness (http://www.handprint.com/HP/WCL/color11.html#valchrom). For example, yellow only reaches its peak, sunny chroma at a very high lightness; at darker values it becomes a dull umber or green. Blue, in contrast, reaches its peak chroma only at low values; at lighter values it appears pale or whitened.

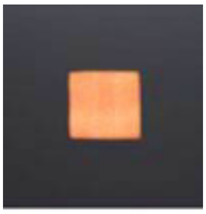
As we have seen, many systems of color harmony the Chevreul system, the Munsell system, the Ostwald system, the Coloroid system have recommended , different hues of the same lightness and chroma. But what happens if we want to find nuance harmonies between yellow and blue? The illustration below superimposes two pages from the Munsell Book of Color (http://www.handprint.com/HP/WCL/color7.html#munsellpages) for a warm hue (middle yellow, 5Y) and a cool hue (middle blue, 5PB).



overlap in two hues from the Munsell Book of Color

a - the peak chroma of blue (at value 4); **b** - the peak chroma of yellow (at value 9); **c** - the highest chroma blue at a value equal to **b**; **d** - the highest chroma yellow at value equal to **a**; **e** - the maximum chroma at which yellow and blue have the same value and chroma; **f,g** - colorant nuance of blue and yellow (see diagram below)

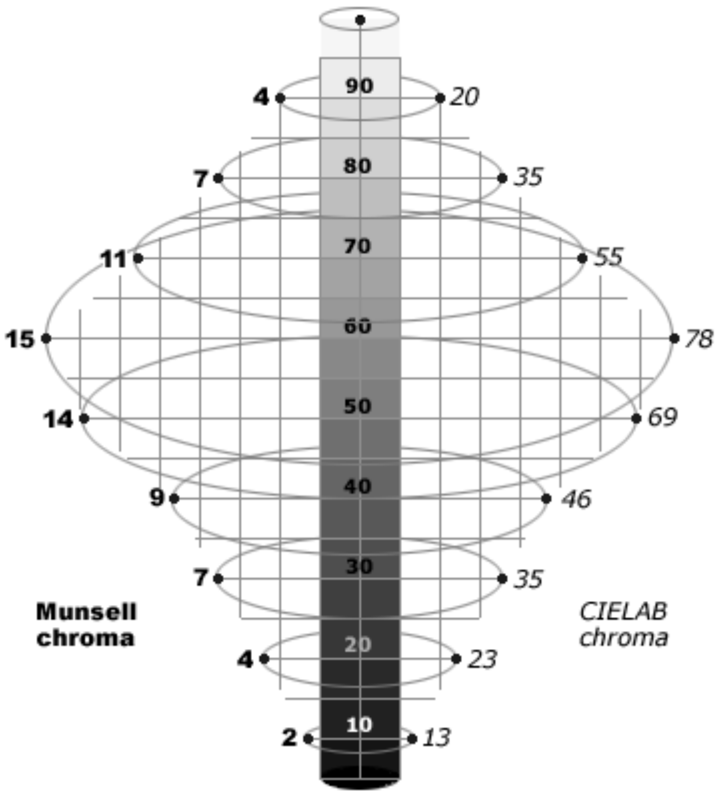
As the diagram suggests, there is a large area of colors (below the orange line) where both a yellow and a blue can be found at matching lightness and chroma, which produces a nuance match. But these nuance matches exclude the peak chroma of both colors, and nearly all the chroma at the light and dark extremes. We end up with roughly a pyramid of chroma, where the most saturated nuance match is near a middle lightness of 6 on the Munsell value scale (point **e**).



luminance contrast and
color chroma

an identical burnt sienna can create visual colors orange, brown or black solely by manipulating the luminance contrast with its surround

In fact, if we consider all hue overlaps in this way, the green intersection between yellow 5Y and blue 5RB (above) defines the area in which a nuance match between *any* two or more hues can be found that is, the volume in which **every hue can be represented at the same lightness and chroma**. I call this the *nuance space*, which can be defined in terms of optimal colors so that it is completely media independent (diagram, below).

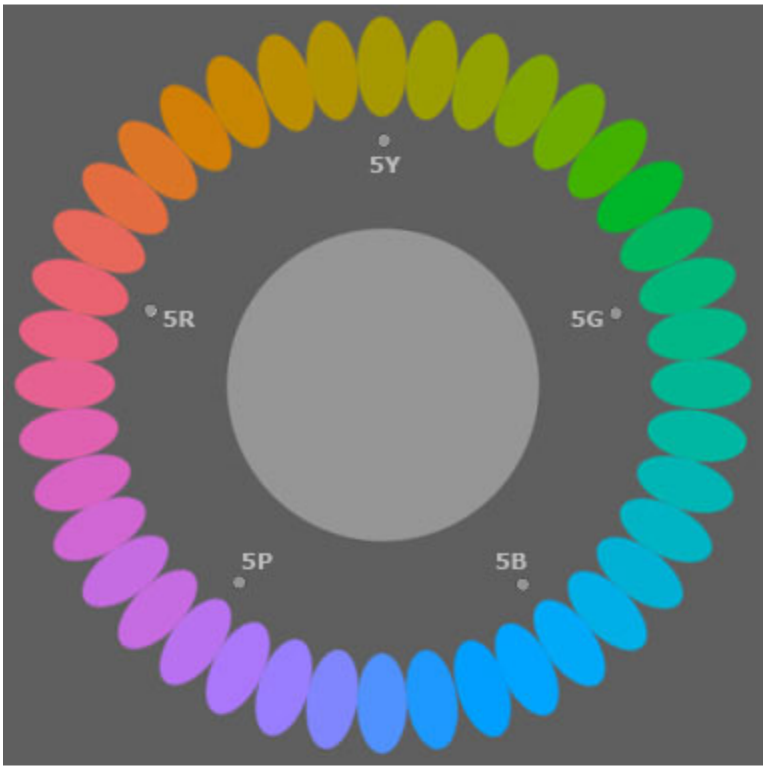


the nuance space

the range of lightness and chroma values common to all optimal color stimuli, expressed in units of Munsell chroma (left) and average CIELAB chroma (right), on a vertical CIE L* scale (grayscale)

Measured within the created by optimal colors (http://www.handprint.com/HP/WCL/color3.html#optimalstimuli), the most saturated possible surface colors, the nuance space has roughly a diamond shaped cross section. It is widest just above a middle gray (**L*** = 50 to 65), and tapers above and below into the achromatic axis at pure white and pure black.

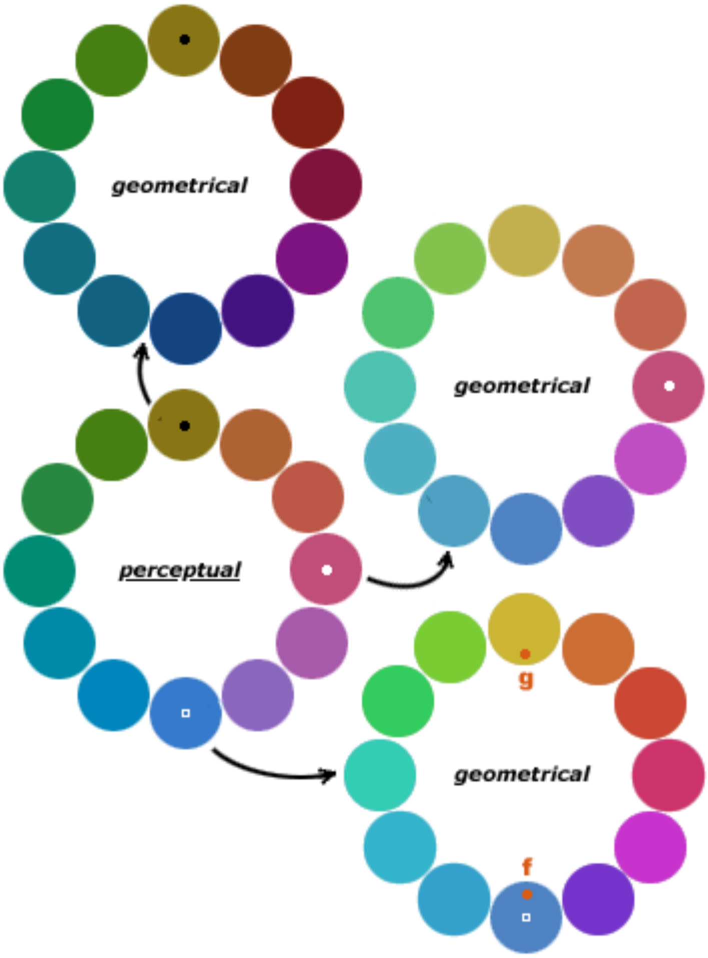
The nuance hue circle at peak chroma is approximately at Munsell value 6 or CIE **L*** 60, a middle gray. To illustrate the range of chroma this hue circle encloses, here are the Munsell aim colors at value 6 (**Lab** lightness 62) and chroma 14 (**Lab** chroma between 60 and 100).



a nuance hue circle

the Munsell hue circle at **V** = 6 and **C** = 14, displayed on a gray **V** = 4; central gray circle is also **V** = 6

The nuance space shown above defines the *perceptual limits* of nuance combinations; the color space defined by actual pigments or dyes, or by the gamut of a display or printer, will be smaller and less regular. In other words, there are two different ways to implement the concept of nuance as perceptual (media independent) chroma limits, and as colorant (media specific) chroma limits. These two approaches yield different nuance color harmonies, as shown in the diagram (below).



two types of nuance

perceptual nuance based on CIELAB **L** = 50 and **C** = 50 across all hues;
geometrical nuance based on (**a**) saturation = 85% and brightness = 50% across all

hues; (**b**) saturation =60% and brightness = 75% across all hues; (**c**) saturation=75% and brightness = 80% across all hues; dots indicate identical colors in perceptual and geometrical nuance rings; letters **f** and **g** identify yellow and blue colors in the Munsell diagram (above)

perceptual nuance equates hues that have the same perceived lightness and chroma, or brightness and saturation, as defined in a perceptually based color model such as the Munsell Color System (http://www.handprint.com/HP/WCL/color7.html#Munsell), the OSA uniform color scales (http://www.handprint.com/HP/WCL/color7.html#OSA-UCS), or a CIE color model (such as CIELAB (http://www.handprint.com/HP/WCL/color7.html#CIELAB)).

colorant nuance equates physical color samples of pure color pigments subtractively mixed with the same relative proportions of white and black pigments, as exemplified in the "triangular" geometries of the Swedish NCS (http://www.handprint.com/HP/WCL/color7.html#NCS) or **DIN** color models; or it equates printer or display colors with the same absolute proportions of additive brightness and saturation, for example as in the Adobe Photoshop color picker.

Colors included in a single perceptual nuance vary significantly in media specific brightness and saturation, which means different hues in a perceptual nuance ring anchor or lead into different colorant nuance rings (diagram, above). In the same way, a colorant nuance ring must contain hues of different perceptual nuance. Obviously, colors in a colorant nuance ring will differ visually from one another more than they do in a perceptual nuance ring, because visual color rather than material color is the ultimate framework for color appearance.

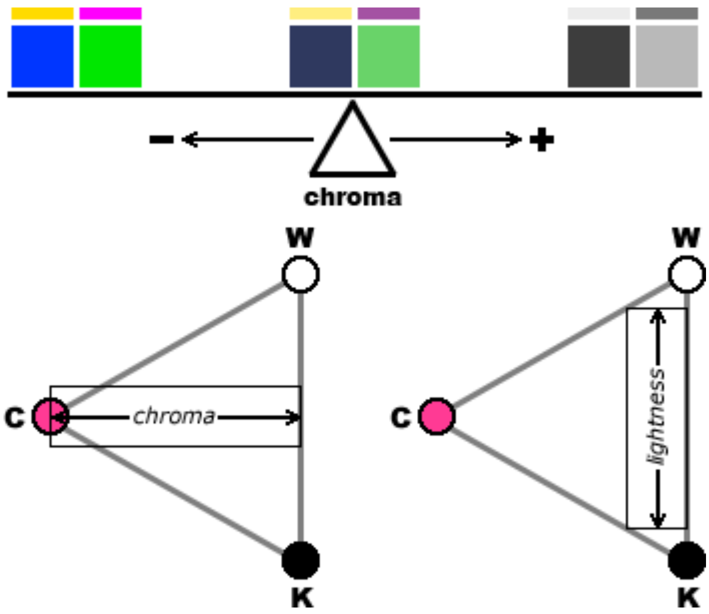
Achromatic Luminance vs. Chromatic Luminance. We now can return briefly to the luminance dependence of lightness and chroma.

Within the nuance space, chroma and lightness are mutually restrictive: if we want high chroma contrasts across all hues, then we are limited to the lightness range around middle grays; if we want high lightness contrasts across all hues, then we are limited to the chroma range near grays. *Outside the nuance space,* chroma still restricts the range of lightnesses, in the sense that high chroma confines the lightness range to very light values (for yellow and orange hues) or very dark values (for blue and violet hues).

Hues by comparison comprise a collection of vibrant individuals, which may explain the emphasis on hue categories, sometimes to the exclusion of lightness or chroma, in traditional formulations of color harmony and color design (*"yellow is the complement of purple", "blue and yellow make green"*, etc.). In any case, like a schoolroom of children, hues require discipline and direction, and to that purpose lightness and chroma exert a powerful controlling effect.

Of the three , lightness is the dominant element (http://www.handprint.com /HP/WCL/color11.html#dominance) in visual design, and contrasts in lightness are the single most reliable and potent method to produce visual contrast. In addition, achromatic lightness variations almost always appear "harmonious" or acceptable in any combination and for any purpose, provided they serve their function for example, the contrasts do not obscure a pattern or text. The "cost" here is that hue is suppressed.

At the other extreme, chroma amplifies all hues to their peak individuality, but at the cost of making lightness variations more difficult to control, in the dual sense that the peak chroma dictates a specific lightness for any hue, and that *chromatic luminance* adds to the apparent *achromatic luminance* (saturated colors appear "brighter"), which obscures the underlying lightness relationships or "value design".



relationship of lightness, hue and chroma in color design

A key image therefore is that chromatic hues are poised opposite achromatic values in a balance, and the fulcrum is defined by the relative contribution of chroma to the color variations. As chroma increases lightness loses leverage in the color design in relation to hue; as chroma decreases, hue loses leverage in relation to lightness.

Context & Pattern. Separate from the sensual qualities of color are its properties as pattern.

Visual Area. The angular dimensions of something as measured from the viewer's eye, the height and width of something relative to the entire field of view, the visual size.

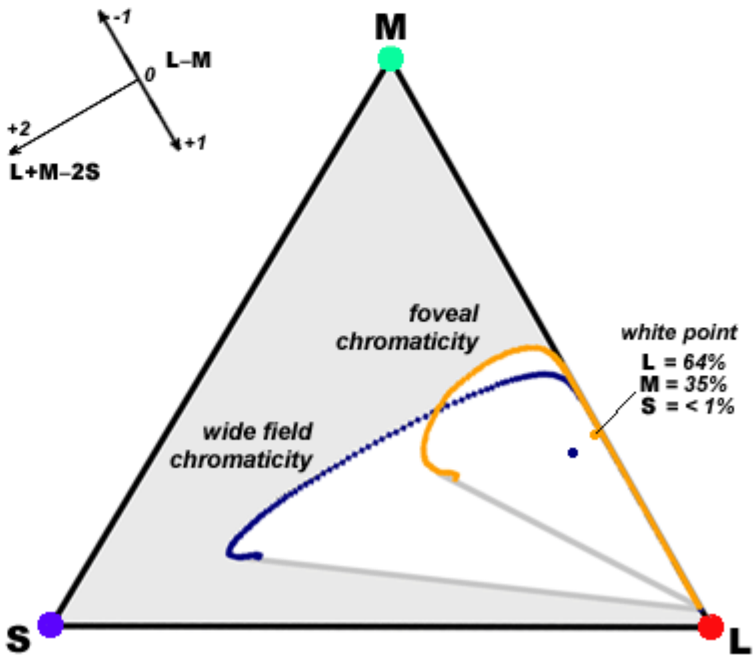
Spatial Frequency. The "spacing" or visual size of color areas. In three dimensional space, spatial frequency (resolution) decreases as the color area is farther away or physically smaller, and increases as the color area becomes closer or physically larger.

Spatial frequency is most familiar through the process of **visual fusion**, which causes colors to mix (in *additive* color mixture) as the color areas get smaller. Increasing distance in space transforms the appearance of objects into structurally or visually related textures. And at extreme distances, texture itself dissolves into pure color (diagram, below).

visual fusion of three different color pairs

The are at the top of the image is made of the same green and red pixels as the area at the bottom, but the color units are too small to see individually: instead they mix visually to make yellow or gray. There is a **fusion threshhold** for every texture, beyond which it is blended by the eye into a single homogenous color. Color TV screens, a distant mountain slope and a sandy beach are all composed of tiny discrete forms beyond the visual mixing threshhold.

However, visual fusion is not the only spatial effect in color perception. Color roughly divides into three domains:



10° (wide field) and 2° (foveal) chromaticity diagrams

10° or wide field color (http://www.handprint.com/HP/WCL/color1.html#chromaticities), within a visual area roughly the size of an orange (or larger) held at arm's length, a common industrial standard for color perception, determines our perception of any large color area a wall, a carpet, an automobile, a vase, a book cover 3 and is only weakly affected by contrast with surrounding color areas.

2° or foveal color, within a visual area roughly the size of a 1 Euro coin or a US quarter held at arm's length, is a common colorimetric or color measurement standard, is somewhat limited in the perception of blue colors and significantly affected by contrast with surrounding color areas.

pixel color, within a very small visual area (such as one pixel in your computer monitor) produces highly degraded color that can be almost completely insensitive to blue hues and very strongly affected by contrast with surrounding color areas.

Visual fusion operates in three dimensional space to produce the following sequence of contrasts between large vs. small or near vs. far visual elements:

pattern > texture > color

Pattern is the covering of a visual area by means of the tiling or repetition of homologous, visually recognizable and smaller color areas. Pattern is always an artificial surface, expressly created for its visual impact.

Texture is the covering of a visual area by means of the random or irregular distribution of very small color areas, or by a uniform repetition of surface irregularities. Texture is typically a natural surface or uncontrolled variation in a manufactured surface, and typically the visual appearance is a report of its material composition or its tactile quality.

Text. Text is the arrangement of standard units of pattern to symbolize language. As pattern, text has been frequently used in architecture, graphical arts and painting, from the Renaissance to the present day, as both decorative and thematic content.

A Color Design Vocabulary. To conclude this long tutorial, I must address the logical gaps created by reliance on only the traditional terms *harmony* and *contrast* in previous color theory. In particular:

color principles have been formulated in terms of , and are therefore detached from the *material variation* of a particular object or environment

color is defined as *colorant relationships* (mixtures of three primary colors) instead of as *visual (perceptual) relationships*; and

design principles have been formulated without regard to the purpose or place in which the colors are displayed.

Let's step back from "color" harmonies defined along the color circle which are really only *hue* harmonies and look at these simple contrasts as **"full color" problems including lightness and chroma**. In an , I proposed that:

Color harmony is the manipulation of lightness and chroma within a given selection of hues so that all colors contribute to an intended visual effect.

This is a break with traditional color theory, where the emphasis is on carefully selecting hues "the color in colors" to produce a color harmony.

Apart from any innovations or insights into color perception or color physics, it seems very clear that any advances in "color theory" will require a more precise and flexible vocabulary to denote the kinds of effects we want to describe as color principles. Herewith my attempt to fill that need.

design frame is the *visual scope of color evaluation;* the boundary around visual design. For a vase as an object, the scope is the vase itself; when the vase is used as an element of interior decor, the frame is the environment in which the vase is displayed.

color palette is the *enumeration of dominant or frequent colors presented within a frame;* the countably different colors (defined in terms of lightness, hue and chroma, rather than just hue) that appear within the frame. For a painting, the palette is the enumeration of the raw pigment colors used to mix all the other colors in the painting.

color dimensionality refers to *the number of colormaking attributes varied within a palette*. A palette that varies only in lightness (monochromatic or achromatic) or hue (nuance) is *unidimensional,* a palette varied only in hue and lightness, or hue and chroma, or lightness and chroma, is *bidimensional;* a palette that varies on all three colormaking attributes is *multidimensional*. Multidimensional palettes include palettes multiplied through pigment mixture, or through complex patterns or textures.

color contrast is the *visual dissimilarity between all colors in a palette*.

This is approximately equivalent to the distance between colors in a perceptual, uniform color space, although the ultimate criterion is the visual color appearance, and not the representation of the colors in any abstract geometry. Colors that provide the largest contrast are widely separated in lightness and chromaticity: strongly saturated colors very different in hue and lightness.

color volume is the *contrast multiplied by the dimensionality of a palette,* the number of dimensions in the palette and the size of the color contrasts produced by the contrasts on those dimensions.

color center is the *color identified as the average lightness and chromaticity of all colors in a palette,* when the colors are combined according to the Newtonian method (http://www.handprint.com/HP/WCL/color2.html#mixingcircle) of weighted averaging.

color unity is a *small volume of pairwise contrasts within a color palette,* typically produced by a common property of light, material or pigment. Unity subdues the visual variety in an architectural space, or the visual impact of a pattern, design or text.

color variety is a *large volume of pairwise contrasts within a color palette*.

color consonance is present when each color appears as or more saturated and luminous when viewed within the color field than when viewed separately on a gray background; **color dissonance** is present when one or more colors seem to produce an unwanted darkening or dulling in the appearance of other colors in a palette.

color gradation is the *number of discrete color mixtures produced by a color palette;* gradation is common in paintings and in many kinds of natural materials.

color balance means that no *hue* appears more dominant or more prominent than any other, by reason of its lightness, chroma or visual area.

color coherence means that all colors are fitted to an underlying pattern, design or text in a way that makes the underlying pattern visually distinct and legible.

I have intentionally excluded the term *harmony* simply because it has been used over the past three centuries with so many different denotations, and with relationship to so many different theories of color design, that it has become hopelessly ambiguous, if not misleading.

Visual Color Examples. Finally, it is important actually to look at different combinations of lightness, hue and chroma in order to identify valid principles of color design. For that reason I have created several large image files.

These 90 image files are online as a library of chromatic induction & contrast (http://www.handprint.com/HP/WCL/IMG/CICH/cich.html).

Readers may also want to browse my image recreation of the OSA Uniform Color Scales (http://www.handprint.com/HP/WCL/IMG/OSA/index.html), as these images present arrays of evenly spaced colors as differently oriented slices through the perceptual color space.

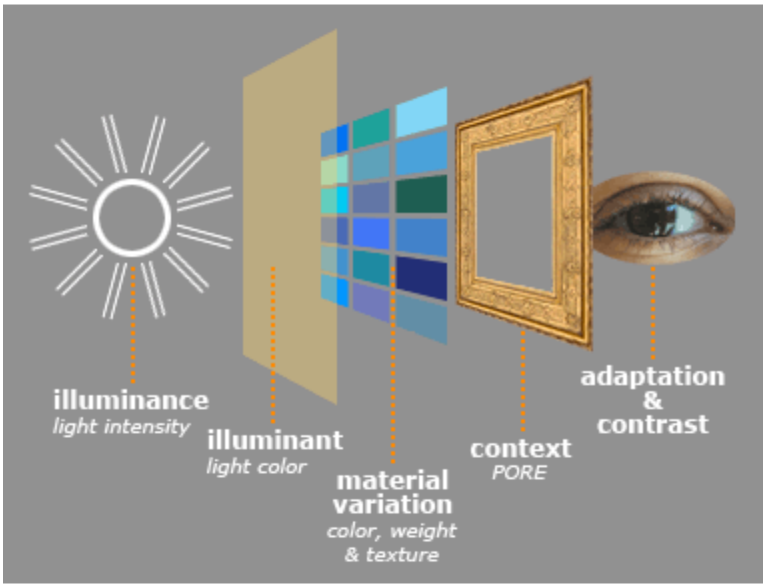
principles of natural color harmony

With the key concepts in hand, let's now formulate the essential principles of a natural color harmony.

Before you tackle this section, you should be familiar with the three colormaking attributes (http://www.handprint.com/HP/WCL/color18a.html#colormaking). Correct understanding of these terms is essential to the color differences I will discuss. In particular, *hue names* refer to colors as they appear in the visible spectrum, including extraspectral purples and red violets. Brown, ochre, pink, olive, etc. are not hues but *colors* produced by darkening or whitening red or yellow hues.

Also, remember that a color contrast viewed on a light emitting computer monitor may not have the same effect as a contrast viewed in light reflecting paints or colored papers. If possible, print out the color examples and compare the visual impact of the paper and monitor versions.

An Empirical Framework. In response I've developed a theory of **natural color harmony** that organizes color in relation to five components (figure, below).



the five components of a natural color harmony

These components are:

illuminance - What is the overall intensity of light (http://www.handprint.com/HP/WCL/color3.html#illuminance) in the environment where colors are viewed?

illuminant - What is the chromaticity (hue and saturation) of the light? What are the color rendering properties of the light? How strongly does the chromaticity contrast with the light in immediately previous light environments?

material variation - What are the materials defining the built environment, the surface environment, the objects in the environment, the landscape or setting? What is their natural, customary or habitually experienced range of colors, defined as a gamut and a palette of surface textures and physical weights?

context - What is the color for? How will the color function or be interpreted in relation to the as surface pattern, as unique object, as representation or as spatial environment (PORE)?

perceptual structure & response - How will the average person perceive the colors in the given situation, in terms luminance adaptation, contrast, color associations and cultural conventions?

My alternative **natural color harmony** unfolds from the answers to one question: how do colors actually combine in everyday perception of the real world? I believe these familiar color combinations help to establish color harmony attributes by shaping the involuntary responses of the eye to light and of the mind to color. I've come to believe that our sense of color harmony is fundamentally based on **the effects of light on color appearance**, on the eye's response to light and color through chromatic adaptation (http://www.handprint.com /HP/WCL/color4.html#chromaadapt), and on the color contrasts that are most important in our perception of surface patterns and spatial relationships.

Foundations of Natural Color.

1. Color is a contextual interpretation of sensory information.

This is basically a caution against thinking about color design in terms of *concept colors,* those abstract, language based, memory anchored color ideas that are neither physical materials nor visual sensations.

We can certainly summarize a desired color in words, or request an ink mixture using a CYMK formula, but we must always anchor our color designs in the actual visual inspection of the color combinations produced by specific materials examined under the intensity and color of light that will be used for their long term display.

2. Color interpretations build on our lifetime experience with all physical environments under all types of light.

In part this cumulative experience is "hard wired" into our visual system, as our infant visual system developed into childhood; in part it is "soft wired" as memory and conception; and in part it is "dynamically wired" as the visual and cognitive capability to compensate for and ignore variations in natural light and variations in the color of surfaces due to shadows, artificial lights, foggy days and so on.

3. The biological adaptations for color perception have been determined by evolution to natural surfaces under natural light.

A substantial amount of the foundation structure of our vision has been inherited from our primate ancestors and, through them, from our mammalian and even vertebrate ancestors. Human photopigments (in fact all mammalian photopigments) evolved from the photopigments of prehistoric fishes.

All these animal visual systems evolved in relation to terrestrial materials under solar light, and these form the bedrock and skylight outlines of color experience.

4. Some part of the coappearance of colors is due to the physical structure of the natural environment and the qualities of natural light.

5. Some part of the coappearance of colors is due to perceptual structure evolved in relation to natural surfaces under natural light.

Complementary shadow colors, contrast and luminance,

6. Modern color experience is a mixture of both natural and artificial surfaces under both natural and artificial light.

7. Some part of the coappearance of colors is derived from the constructed environment and the effects of artificial light.

8. Colors that consistently coappear in color experience are perceived to "go together" in artificial color arrangements and color design.

We accept the natural world as natural, and find nothing objectionable in its color combinations though we may recoil from the substances the colors signify!

9. Colors that have been habitually perceived to coexist in specific environments are learned as significant signs of those environments.

Environments have a deep structure that affects their color palette. Artic environments are characterised by copious frozen water; deserts by an abundance of silicates and iron oxides; forests by plants and trees; tidal pools by ocean water and foam. In each environment the light of the sky is different, due to differing combinations of humidity, suspended ice crystals or dust, and the filtering of light through leaves or reflected from wet surfaces.

10. Three forms of color response the biological, the natural, and the artificial coexist and dynamically influence one another in color experience.

The previous principles make it clear that we cannot account for color harmony or contrast solely in terms of "primary" color combinations, or color series within a perceptual color solid, or the coappearance of colors in nature, or any other one dimensional color harmony scheme. Color is a densely determined experience, and we gain control of color to the extent that we are able to take its various dimensions into consideration.

The Perceptual Natural Color Hierarchy. Colors do not appear in our experience with equal frequency across all light environments and in completely random asociation with other colors and surface materials. Instead, our color experience is structured by the natural and artificial environment, and our cumulative color experience forms the foundation of our sense of color harmony.

X. *Novelty* is the cumulative frequency of a specific visual color experience within the totality of color experience.

Every material color, across all variations in illuminance and illuminant, defines a group of visual color experiences. These experiences form part of the total color experience across the lifetime of the individual.

Material colors are determined by the facts of physical reality the structure of molecules and crystals, the density of surfaces and films

X. Color novelty is largely perceived in relation to the color experience provided by recognizably distinct physical objects, contexts or situations.

Because color perception is designed to attribute colors entirely to the quality of objects, separate from the effects of perception and illumination, novelty becomes anchored in our experience of objects rather than the perceptual range of concept colors.

The color white has a relatively low color novelty, considered within the domain of all colors perceived across a lifetime; but the color white, appearing as a zinc salve applied to a sunburned nose, appears highly novel in the context of the color experience provided by all faces perceived across a lifetime.

X. Across all contexts, colors progress from less novel to more novel in a hierarchy of decreasing color frequency, approximately as follows:

a. **luminance adaptation** [primitve: *ganzfeld*]. The ganzfeld is the peculiar achromatic, nonspatial visual experience that is produced after a few minutes by a single seamless color filling the entire visual field. Even if the color field is strongly chromatic, all visual color disappears in a ganzfeld. At the same time, a ganzfeld can be produced by a visual field at any illuminance level. This illustrates that the eye fundamentally responds to luminance, through the mechanisms of luminance adaptation, separate from any color perception.

b. **illuminant** [primitive: *gray*]. The color *gray* signifies both the average luminance of surfaces, after luminance adaptation has taken effect, and the effect of chromatic adaptation to eliminate the color bias created by the illuminant. Gray is the central color for all color experience, the anchor point for chroma and lightness variation, and the hub of hue variety.

c. **lightness variation** [primitives: *white anchor, light/dark contrast*].

d. **warm/cool contrast** [primitives: *low chroma, warm/cool contrasts*].

e. **natural colors within the nuance solid**.

e1. **warm color variations** [primitives: *moderate chroma, red to yellow hues*].

e2. **cool color variations** [primitives: *moderate chroma, green to blue hues*].

f. **organic colors outside the nuance solid** [primitives: *all hues, moderate to high chroma*].

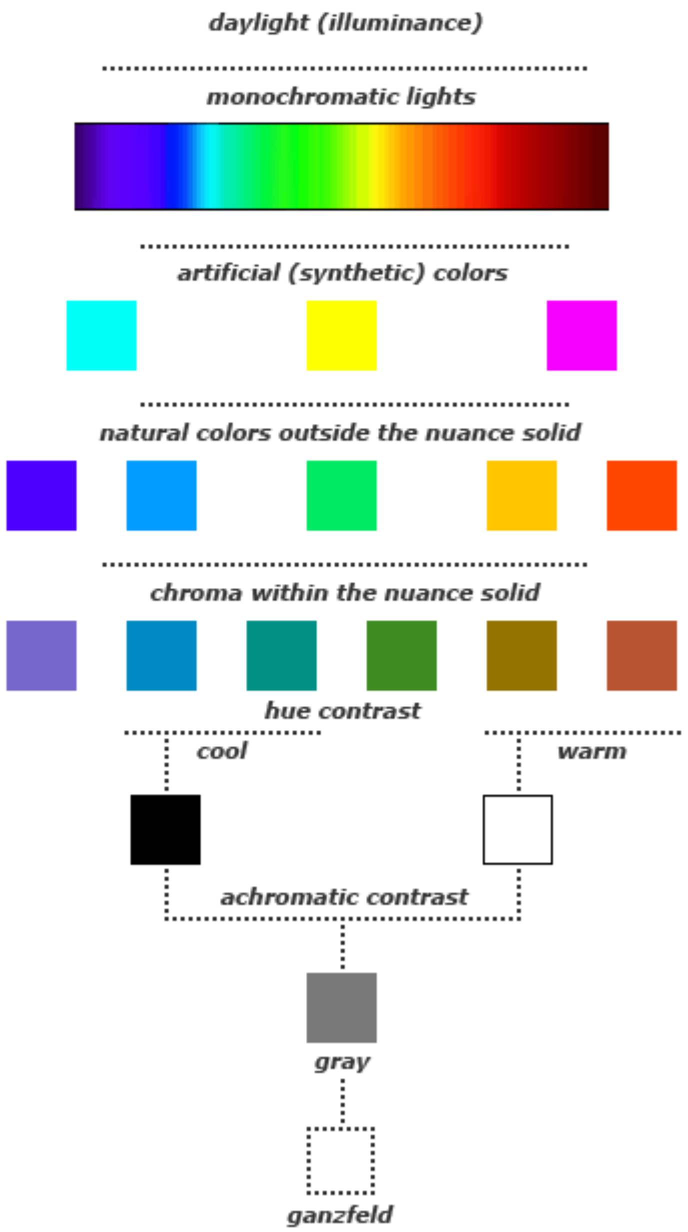
g. artificial display colors [primitives: *processed or synthetic pigments*].

h. refraction colors [primitives: *natural iridescence, rainbow, prism spectrum*].

i. solar image [primitive: *Urlicht, illuminance as luminance*].

Blah.

This experience is summarized as a *natural color hierarchy* (diagram, below).



the natural color hierarchy

These components are:

gray represents the average reflectance of all surfaces in an environment the average quantity of light reflected to the eye. It is the *surface reflection of illuminance*, and the *contextual anchor of adaptation*. Our experience of this gray is continuous.

achromatic contrast represent the variance or variety in the reflectance of surfaces in an environment the range of surface lightnesses. It is the *surface absorption of illuminance,* and is the signal of material qualities separate from both illuminance and chromaticity. Our experience of achromatic contrast is also continuous, and it represents our dominant source of visual information.

colors within the nuance solid represent the *habitual range of natural surfaces,* and of all artificial materials that mimic the natural color range. Our experience of the nuance solid varies with the type of environment we are in, and its volume increases with increasing illuminance, but over our life experience we acquire a definite conception of these color limits.

natural colors outside the nuance solid comprise our experience of exceptional but organic or mineral colors; to achieve high chroma these colors are also associated with a specific lightness or brightness.

artificial (synthetic) colors are those colors that only appear in synthetic materials; among these are the subtractive "primary" colors cyan, magenta and green yellow, which are extremely rare in natural color experience.

monochromatic lights are almost exclusively limited to transmitted and strongly filtered light, refraction or interference colors, and artificial light sources.

daylight is the brightest and most neutral light source in the light environment.

These are based on the relative frequency of color transitions within color experience.

X. Color novelty signifies scarcity in natural color and investment (labor, cost) in artificial color.

X. Environments with a high proportion and/or wide variety of novelty colors are *rich* color environments. **Environments with a high proportion and/or homogeneity of common colors are *impoverished* color environments**.

The Influence of Spatial Factors. After luminance and chromatic adaptation and sensation, spatial interpretation is the most dominant factor in color perception. Its effects neatly divide into *two dimensional* and *three dimensional* color interpretations many of them "hardwired" in our color experience.

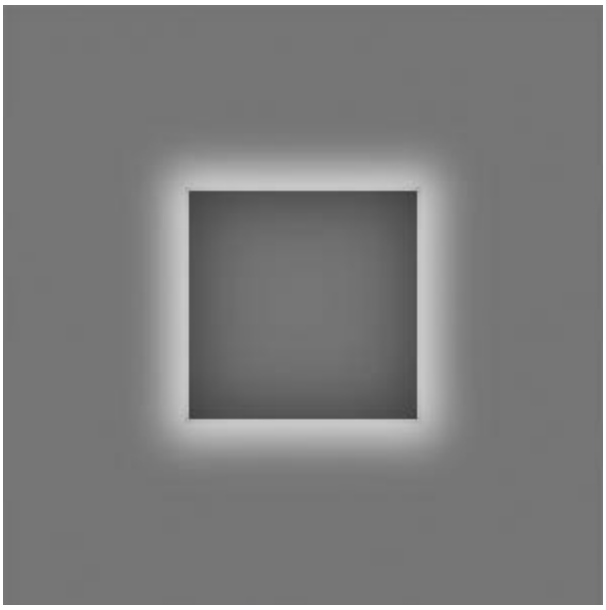
Two Dimensional Color Effects.

X. From the sensations of color experience, color vision perceives surfaces as contours and envelopes of physical form, and adjusts visual color to reinforce the surface interpretation.

<u>Visual Size (Angular Dimension)</u>. In general, smaller visual units produce an increase in lightness contrast and a corresponding reduction in chromaticity. At the extreme, very small colors fixated at the fovea can appear lacking in blue content.

Surface integration.

The Cornsweet Effect.



the cornsweet effect

thus.

The Watercolor Effect. This is a variation of the Cornsweet effect, in which chromatic content propagates over a neutral surface from a chromatic edge.

the watercolor effect

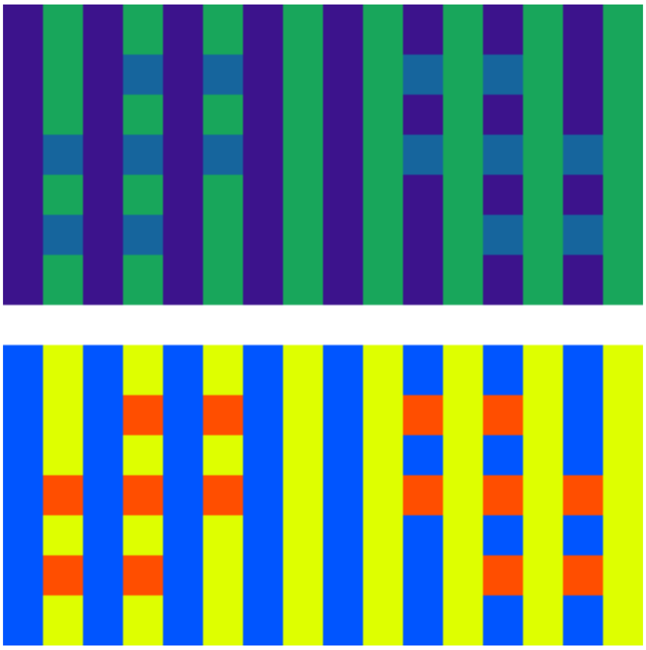
thus.

Spatial Separation.

The White Effect.

the white effect in lightness contrast

thus.



the white effect in hue and chroma contrast

thus.

The Benoit Effect.

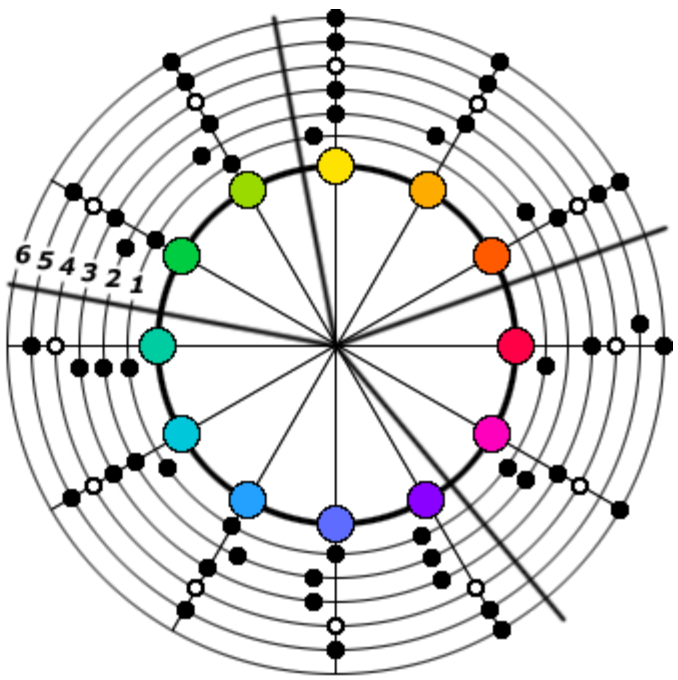
the benoit effect

thus.

The Significance of Materials. as brought out in the Basic Forms of Color (http://www.handprint.com/HP/WCL/color4a.html).

Large Area Color Contrasts. I present both the traditional "square in square" contrast diagrams inherited from color theory texts (by Josef Albers (http://www.handprint.com/HP/WCL/book3.html#albers) especially).

I've augmented these electronic examples with visual comparisons in daylight of tertiary paint colors applied to white bristol board, arranged as "square within square" contrast patterns, the central squares 3" wide on backgrounds 9" wide, producing a 1:8 ratio between the visual areas. (The paints I used were (1) benzimida yellow, (2) isoindolinone yellow, (2) cadmium scarlet, (4) quinacridone magenta, (5) quinacridone magenta+cobalt violet, (6) dioxazine violet, (7) ultramarine violet BS, (8) phthalo blue GS+cobalt blue, (9) phthalo cyan+cobalt teal blue, (10) phthalo green BS, (11) phthalo permanent green light, and (12) phthalo yellow green+benzimida yellow. See the complete palette (http://www.handprint.com/HP/WCL/palette1.html) for paints matching these color names.)



summary of contrast comparisons

1: analogous; **2**: near analogous; **3**: tetradic; **4**: triadic; **5**: near complementary; **6**: complementary

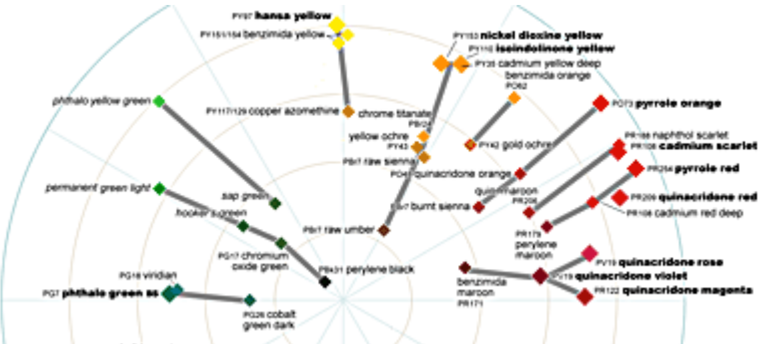
I became interested in these triadic relationships from the beautiful coloring of papaya fruit, which can be both orange and green at the same time. Of course, these harmonies are partly due to the absence of the third "triadic" color, producing an "imbalanced" sampling from the hue circle.

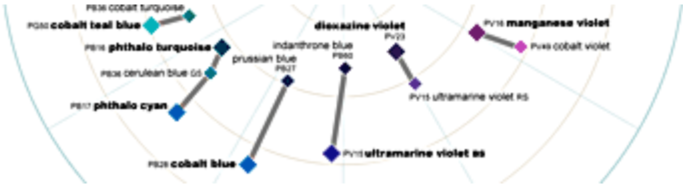
Let's now look at color contrasts from the perspective of including lightness and chroma. The objective is to illustrate the effect of different combinations of lightness, hue and chroma, and to look for useful principles of color design.

Small Area Mixture Relationships. , and that reveal the relative dominance among three or more colors at high spatial frequencies (http://www.handprint.com/HP/WCL/color4a.html#spatialfrequency) (small visual size).

Color in Materials. My objection to these color generalizations is that they treat color in the abstract. As I've argued on many pages of this site, I think this is a misleading way to talk about *sensations* and *experiences*, and glosses over basic issues of color design and the **** process.

An example is the opportunity to use **pigment harmonies** in your ****s. These are created by two pigments that *share a single colormaking attribute but contrast on other color features*. This varies the shared attribute across other color dimensions, creating a "family resemblance" among them all. The most expressive and useful are what I call **pigment siblings** two pigments that have the same hue but differ widely in chroma, value, transparency and texture.





pigment siblings around the hue circle

for details see the pigment locations in the artist's hue circle (http://www.handprint.com/HP/WCL/cwheel06.html)

Most of these sibling pairs differ on all four of the most important pigment attributes: value, chroma, transparency and texture (they are all identical on hue).

I use these siblings in two ways: (1) to vary the value, chroma or texture of a color without mixing with black, gray or a contrasting mixing complement; and (2) to create parallel bands or "scales" of color mixture with matching paints of another hue.

For example, when **** figure nudes, I really like **burnt sienna** as the primary flesh color for sunkissed California skin; its pigment sibling **cadmium scarlet** brings a remarkable lustre to warm shadow areas. (Both pigments hue shift (http://www.handprint.com/HP/WCL/pigmt8.html#hueshift) in tints, but the burnt sienna goes markedly toward yellow, while the scarlet shifts slightly toward red, creating a lovely yellow/pink contrast.) Blending the two pigments produces a striking transition in chroma while providing greater color nuances in tints. Or, when **** seascapes, I like **cobalt turquoise** as the base for many water mixtures, but use its brighter, whitish pigment sibling **cobalt teal blue** to show areas of brightened, more active or less turbid water.

For the parallel scales of color mixture, consider the sibling pair **ultramarine blue** and **indanthrone blue** with the pair **phthalocyanine cyan** and **cerulean blue GS**. As the ultramarine is mixed with the phthalo, the color shifts from dark to light and from textured to smooth across a wide span of blue hues. The same span is covered by their sibs, and with the same lightness and texture contrasts, but at a lower chroma. These parallel color bands can produce distinctive and very legible color contrasts within an overall analogous color scheme. The parallel scales created by **quinacridone carmine** and **venetian red** with **cadmium yellow deep** and **quinacridone deep gold** provide a very effective contrast on the "warm" side of the color circle.

The artist's hue circle makes it easy to find hue siblings; the artist's value wheel (http://www.handprint.com/HP/WCL/vwheel.html) can help you find similar groupings of pigments with the same lightness or value (value siblings). Matches such as the Tiepoloesque **cadmium orange**, **copper azomethine** and **cobalt teal blue**, or the brooding **quinacridone carmine**, **cobalt blue deep** and **phthalo green BS** can produce gorgeous, rich color mixtures at full strength strong changes of hue, at the pigment's maximum chroma, without any significant variation in value. The overall effect is flat and highly decorative, as hue becomes the main variation across color areas.

The resources here are quite subtle. I was struck, for example, with the way Marc Chagall produced a unique color tension by mixing a visually similar pale yellow from either yellow ochre or cadmium yellow; the ochre gave the color a fleshy warmth that the cadmium met with a lifeless sheen; Chagall also seemed to contrast viridian with phthalo green. (These are, incidentally, effects that are entirely lost in the color reproductions in the exhibition catalog.) Treating "colors" in the abstract means these kinds of effects slip entirely from your grasp.

design guidance

Basic stuff.

Hues Are Promiscuous. Perhaps the most important principle in full color harmony is that there are **no limitations on our selection or combination of hues** in color design:

Given the right combination of chroma and lightness, any selection of hues can be made harmonious in terms of almost any intended contrast or design effect.

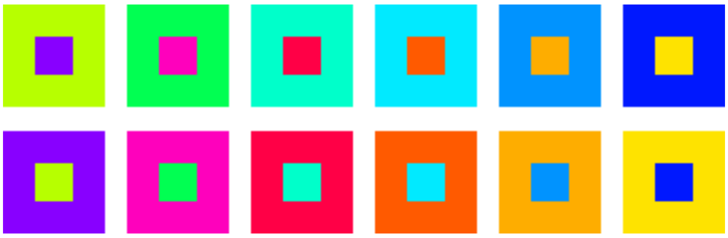
The inherited lore about color "personalities", color symbolism and the effects of color on mood or task performance are typically dependent on a specific hue presentation (in terms of lightness and chroma). Thus, *red* (meaning a saturated red) is often said to be "arousing", while *pink* (a whitened red) is said to be "delicate" and *maroon* (a darkened red) is said to be "elegant". Same hue, different effects.

The intended contrast or design effect may exert some constraints on hue choices, but these are generally pretty weak. Legible text provides a good example: so long as there is a large lightness contrast between words and page, any two hues can be used to display text, though colored text would generally be found desirable in a marketing brochure but distracting (and needlessly costly) in a dictionary.

Hue Contrasts Are Not Equivalent. The fact that hues can be freely combined in almost any color design or color contrast application does not mean that the contrasts will be equivalent:

Hue contrasts, including contrasts between complementary hues, are qualitatively different at different points around the hue circle.

To illustrate this issue, the diagram (below) presents the six complementary hue pairs of the tertiary hue circle (http://www.handprint.com/HP/WCL/color13.html#tertiary), with the lightness of each hue determined by the maximum chroma (saturation) possible within the gamut of your computer monitor.



visual complementary contrasts at maximum saturation

all hues at the same nuance; lightness differences are determined by saturation alone

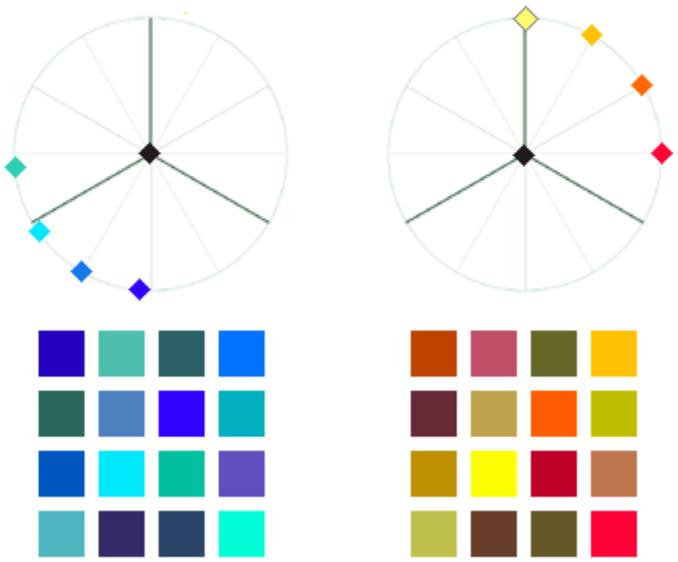
For me there is something strident and stifling in the visual complementary contrast between deep red and teal blue (third from left), and this hue contrast, which represents the **a+/a** dimension in CIELAB (http://www.handprint.com/HP/WCL/color7.html#CIELAB), is subjectively the most intense chromatic antagonism in the color space. Those hues just do not want to get along!

In contrast, the pairing of violet and yellow green (far left) creates a peculiar sense of repose and sweetness (the Pre-Raphaelite painters (http://www.handprint.com/HP/WCL/artist10.html) were especially fond of it). The contrast between blue violet and yellow (far right) is dominated by the extreme lightness contrast between the two hues, while the orange and blue pairing next to it creates a pronounced but decorative contrast on all color attributes. These contrasts produce very different effects that can be emphasized or minimized by adjusting lightness and chroma.

Hue Regions Are Not Equivalent. A third principle in full color harmony is that:

Altering the lightness and chroma of hues does not produce perceptually equivalent effects within different regions of the hue circle.

This is obvious if we compare two "analogous" hue sections of the hue circle, defined as four adjacent points of the tertiary hue circle (http://www.handprint.com/HP/WCL/color13.html#tertiary), in which the same variations in chroma and lightness have been applied to the hues.



analogous design palettes from different sections of the hue circle

We see at a glance that the variety of colors possible with the "warm" palette (from yellow green to red orange, wheel points 1 to 4 (http://www.handprint.com/HP/WCL/color16.html#tourwheel)) is much richer and more varied than an equally large section from the "cool" side of the color circle (wheel points 7 to 10), primarily because of the appearance of green gold, green umber, brown, ochre and maroon.

These *qualitative differences among hue contrasts* are the reason circular "color calculators" or abstract design patterns such as "split complementary palette" are ineffectual design tools. The color space is not as symmetrical as a circle or as homogenous as cookie dough, so using cookie cutter color concepts won't get you very far.

Summary Points. So what are the principles we have come up with? Here is a summary of the main points:

lightness and chroma are the most powerful contrast stimuli, as judged by the amount of apparent color shift they can produce in simultaneous color contrasts (chromatic induction (http://www.handprint.com/HP/WCL/color4.html#chromainduct)).

different hues reach their maximum chroma at different lightnesses. Keep in mind the lopsided differences between yellow and blue (as shown in this figure (http://www.handprint.com/HP/WCL/color7.html#munsellpages)), which characterize other hue contrasts (http://www.handprint.com/HP/WCL/color7.html#piggamut) as well. This is an obvious point an intense yellow is lighter valued than an intense blue, an intense red has a higher chroma than an intense blue green. Yet most of the peculiarities of the color space arise from this basic difference among hues. (For an explanation of why this difference arises, see this discussion (http://www.handprint.com/HP/WCL/color11.html#valchrom).)

there is limited intersection between two hues on chroma and lightness (saturation and brightness), and this area of overlap generally grows smaller as hues become more widely separated on the hue circle. If we combine this point with the points above, we see that the most powerful contrast effects arise from the color attributes that are most difficult to match across different hues.

the greatest chroma overlap occurs around middle gray. Every hue can be darkened to black or lightened (diluted) to white to match any other hue, but these changes dull the chroma (saturation) of the color. Only a roughly triangular area along the gray axis of the color space provides common perceptual nuance across all hues (diagram, below).

warm paints have the highest chroma range. Most warm (red to yellow) pigments have a higher peak chroma than their complementary cool (green to blue) paints, as shown in the artist's hue circle (http://www.handprint.com /HP/WCL/cwheel06.html). This means we must dull a red to yellow color in order to match the maximum chroma of the complementary cool hues.

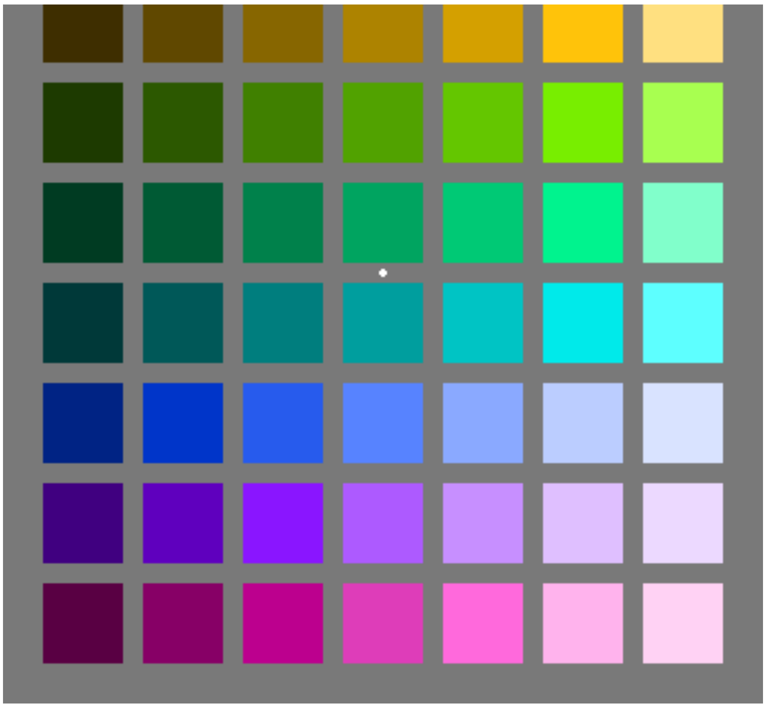
changes in chroma have a greater visual effect in warm hues. However we are limited in our ability to match warm and cool hues because the dulling or darkening of warm hues transforms them into subjectively different colors, the ochres and browns (http://www.handprint.com/HP/WCL /color12.html#unzones). If we want to retain the characteristic hue appearance of a warm color, we are even more restricted in the range of lightness and chroma values we can choose to match the cool (blue and green) hues.

1. Color attributes are qualitatively different across different hues.

2. These qualitative differences arise primarily for three reasons: (a) the maximum chroma of each hue occurs at a different lightness; (b) warm color paints are typically more intense than any of their complementary cool color paints; and (c) changes in chroma have a greater visual impact in warm than in cool hues (because of unsaturated color zones).

3. Because of these differences, color matching is restricted in several ways; there is only limited overlap in chroma and value between two hues, and this overlap is different for different hues.

4. Afterimages do not equal original colors. Afterimages are much paler (lighter, less saturated) than the stimulus colors, implying that the complementary color relationship is not symmetrical.



afterimagesstare fixedly at the white dot for about 15 seconds, then *mouseover* to see the afterimage colors

4. Color harmony depends to a substantial degree on the lightness and saturation of all the colors: among the most harmonious combinations are varying the lightness within a constant hue or a cluster of related hues (especially at low chroma), or presenting a wide range of hues having the same lightness and chroma (color *nuances*).

5. The impact of lightness and chroma depend on the image context in which the colors appear; the representation of patterns and objects (http://www.handprint.com/HP/WCL/color8.html#patterneffects) can affect color harmony, as can contrasts between color areas interpreted as foreground and background, or focal area and surrounding context, or areas of warm and cool color.

6. Color harmony is improved by changes in lightness or chroma *relative to* the range of a specific hue: in general contrasts between hues at opposite ends of the CIELAB (http://www.handprint.com/HP/WCL/labwheel.html)

a+/a- dimension are different from those between hues at opposite ends of the **b+/b-** dimension. These effects resemble the ways that changes in an illuminant or color adaptation in the mind produce constant relative changes in all colors in view.

For a related discussion in the context of near neutral colors, see this page (http://www.handprint.com/HP/WCL/tech17.html#design).

Color is fundamentally *representational:* colors are much more like sounds, which indicate the effects of material objects on energy, than like tastes, which have an internal, physiological valence (sweet vs. sour).

This inherently representational attribute of color means that color is simply variety in light, which is the physical energy that makes optical representation possible. Without radiant energy there is no light and no color.

However color perception is like tastes in the sense that both are **categorically divided**: color and taste are both much more categorical than sound, more easily reduced to sensory "primitives" and better defined by abstract dimensions such as sweet vs. sour.

2. Color representation is two dimensional: color is created by the qualities of a material object and by the qualities of the illumination cast on the object.

Here again color is like sound, which is created by materials but is strongly affected by our distance from the source of the sound, and again unlike taste, which is always "in the mouth".

A different kind of variation is produced by changes in the sensation *power,* which is produced in all sensory modalities by a change in material concentration or physical energy. Thus, the loudness of a sound increases through being closer or being louder.

Color is similarly an object in itself and a light falling on the object, which is the illuminant. An extreme illuminant appears as a veiling or filtering of all environmental colors, perceptually almost indistinguishable from viewing the environment through a strongly tinted glass, except that filtered light appears subjectively darker. A strong chromaticity also has the quality of neutralizing surface colors opposed to it, and enhancing the saturation of surface colors similar to it.

This leads us to anticpate two basic dimensions of color experience: **color concentration** (analogous to the loudness or energy of a sound) and **color contrast** (analogous to our distance from a sound source). Color concentration would appear as hue purity (http://www.handprint.com/HP/WCL/color2.html#huepurity) and color contrast would appear as brightness or lightness). These contribute separately the intensity and clarity of color appearance.

3. Vision is adapted, by our genetics and experience, to respond to the range of colors defined by *natural surfaces* viewed in *natural light environments*.

Everything science has learned about animal perceptual capabilities indicates that they are often exquisitely adapted to the task of survival within a specific environmental niche: we see what is important to our survival and vitality. We now can interpret human color vision in terms of material and light environments.

Humans have a broad environmental adaptation, but we are basically primates that live in a terrestrial ecology, arboreal or grassland, under daylight illumination. In constructed environments we are most comfortable at illumination levels in the range of 50 to 500 lux. Darker illuminances are comfortable for rest, brighter ones for meticulous tasks.

The natural terrestrial surfaces are soils, rocks, all kinds of vegetation, water and the sky perceived as a surface or dome over our heads. Our species colors are basically black, brown, red or yellow (in hair color) and muted shades of red orange (in skin). The natural light sources are the sun, the sky, and variations in the colors of sunlight and skylight produced by time of day, season and atmospheric content (smoke, dust, clouds or fog).

Under bright, clear illumination the sky appears to be a very saturated blue, and all foliage colors appear as saturated as possible, which is enhanced by "yellow" wavelengths. Foliage greens reflect in the middle wavelengths but also in the near infrared, which makes YELLOW light the optimal illuminant after WHITE. Surface yellows are produced by the union of "red" and "green" wavelengths, or **L** and **M** cone inputs. Thus it is especially beautiful to be in a meadow or garden in the late afternoon, when the light begins to yellow, and in bright sunlight, when all floral hues are most saturated.

4. All color information is transduced (made sensible) through a two dimensional surface of four photoreceptors (L, M, S and V), operating within optical imaging centered on the optical axis, compressing a large luminance range into a smaller sensory space.

Everything science has learned about animal perceptual capabilities indicates that they are often exquisitely adapted to the task of survival within a specific environmental niche: we see what is important to our survival and vitality. We now can interpret human color vision in terms of material and light environments.

5. The adaptation priorities in color vision are: scene illuminance adaptation, surface luminance adaptation, grayscale anchoring, chromatic adaptation, color constancy.

Scene illuminance is the total light falling on visible surfaces from all light sources. Although source luminance is typically visible as surface highlights, it also appears as contrast in lightness and colorfulness.

Within a given luminance adaptation, color vision establishes the lightest valued achromatic surface as the "white" standard, with a subjective lightness above 90. This anchoring is relatively independent of surface area. There is also an anchoring on a gray value that gives the luminance variations a complete grayscale value.

The eye attempts to adjust to the chromaticity of the average illuminant, so that an achromatic surface appears gray or neutral, and does not show the chromaticity of the light source.

In cases where the chromaticity of the illuminant is very strong, the subjective sense of colored light does not disappear, but familiar objects retain their local color as if seen through a colored glass or gel filter.

5. The visual system is powerfully adapted to minimize color variations due to natural light variations.

We generally do not perceive the color or *chromaticity* of the natural illumination, primarily because it has a vastly smaller behavioral relevance compared to the qualities of the physical objects and people that surround us.

The largest natural illuminance contrast is between daylight and darkness, or the range from photopic through mesopic to scotopic vision.

We generally do not perceive the color or *chromaticity* of the natural illumination, primarily because it has a vastly smaller behavioral relevance compared to the qualities of the physical objects and people that surround us. But there may be implicated color shifts that we do not perceive directly as *color shifts* but rather as *illuminance levels*.

7. Color is primarily a phenomenon of *luminance contrast* around a *constant illumination*.

The importance of this dimension is revealed in the fact that it performs three separate functions in our color experience. It determines (1) the perception of self luminous lights from light reflecting surfaces, (2) the appearance of surfaces (or lights) as dark (dim) or light (bright), and finally (3) the perception of surfaces as illuminated or shadowed.

Perceptual dimensions of brightness and lightness.

Paradoxically, contrast is enhanced by behaviorally minimizing luminance variation: we do not look directly at light sources or highly reflective surfaces, and the visual system is adapted to minimize flare.

8. Experienced as chromaticity, luminance variation within a constant illuminance level is established as a color contrast from WHITE toward BLUE VIOLET.

WHITE is a surface color that lacks any chromaticity; which means both that it is an achromatic surface *and* that we are completely adapted to the chromaticity of the illuminant.

This association between darkness BLUE VIOLET is reflected in the design of the visual system and in natural color experience in four ways: (1) the **S** or short wavelength photoreceptors do not contribute to luminance perception (http://www.handprint.com/HP/WCL/color1.html#psf), (2) the **S** receptors are perceptually more sensitive in the perception of dim or dark colors, (3) the natural light transition from illumination to shadow is associated with an illuminant shift from direct sunlight (which is "white") to skylight (which is "blue); and (4) the natural light transition from daylight to darkness is generally perceived as a shift from a white toward a bluish illuminant, for example in the color of white surfaces viewed under moonlight or starlight.

9. Experienced as chromaticity, chromaticity adaptation is judged as a natural light contrast between YELLOW and BLUE VIOLET.

If the illumination has any perceptible color (rather than appearing colorless or WHITE), then YELLOW is the chromaticity with the optimal color rendering (http://www.handprint.com/HP/WCL/color12.html#colorrendering) attributes. Under "yellow" (broadband "green" to "red" emittance spectrum), a blue violet material color (such as ultramarine blue) appears BLACK.

This is also shown in light mixture tinting test (http://www.handprint.com /HP/WCL/color2.html#lighttint), where very large quantities of yellow light are necessary to tint or discolor a white light, but only a tiny amount of blue violet light is needed to create a tint, which subjectively appears as a *darkening* of the light.

Similarly, if we think of *luminance tinting* as a large contrast in color/surround luminance, then a 30:1 to 300:1 luminance contrast is necessary to produce an appearance of florence (http://www.handprint.com/HP/WCL /color2.html#tinttest) (illusory emittance) in surfaces coated with a saturated purple, blue or red pigment, while a luminance contrast of 10:1 to 2:1 is sufficient for hues from CYAN to ORANGE.

10. YELLOW (R+G) is the chromaticity of high illumination and RED (R) is the chromaticity of low illumination.

From YELLOW as a WHITE surrogate, the natural light transition is toward the RED of sunset or sunrise.

The physiological basis for this association is that YELLOW is defined by an approximately equal stimulation of both the **L** and **M** cones, indicating broadband radiance, while RED is produced by stimulation predominantly to the **L** cone, which can only happen when light is concentrated at the dimly perceived "red" end of the spectrum. The WrightBrindley effect (http://www.handprint.com/HP/WCL/color4.html#yellowbalance) also demonstrates a color process shift from red toward green as illuminance increases from near scotopic to photopic illuminance.

11. The superordinate dimension of luminance adaptation from photopic to scotopic illuminance levels is defined by the sensitivity balance GREEN vs. RED VIOLET (BLUE VIOLET + RED).

In the spectral band of our peak photopic sensitivity (http://www.handprint.com/HP/WCL/color1.html#psf), GREEN is the inherently bright color of increasing, broadband illumination or illumination with a green chromaticity, whereas RED VIOLET is the inherently dark color of decreasing illumination or wavelengths located at the insensitive extremes of our visual capabilities. Trezona's tetrachromatic matching (http://www.handprint.com/HP/WCL/color4.html#trezona) measurements, expressed in a trichromatic space, define an adaptation axis from 530 nm to c530 nm.

12. High scene illuminance is associated with the colors WHITE and WARM, with strong lightness contrast (Stevens effect (http://www.handprint.com/HP/WCL/color4.html#stevenseffect)), and

with high chromaticity (Hunt effect (http://www.handprint.com /HP/WCL/color4.html#hunteffect)); low scene illuminance is associated with the colors BLACK and COOL, with low lightness contrast, and reduced chromaticity.

The surface hues achieve their maximum saturation only through an apparent lightness contrast with the surround or the adapted scene illuminance. It is not possible to see the colors OCHRE, BROWN or GRAY as an isolated light source: the lights only appear dimmer or more diffuse. These colors only appear in material colors

13. High lightness contrast (higher scene brightness), is necessary for the appearance of maximum chroma WHITE, YELLOW, ORANGE, RED, GRAY and BLACK; low lightness contrast (greater scene darkness) is necessary for the appearance of maximum saturation (RED VIOLET, PURPLE, BLUE VIOLET, BLUE and BLUE GREEN.

The combination of scene illuminance and color/surround lightness contrast is necessary for the appearance of maximum saturation, with average lightness specifying the scene illuminance and color saturation identifying the lightness contrast.

Each hue has a characteristic lightness at which it achieves its maximum chroma as either a material or theoretical surface. In both surfaces, this peak saturation is very closely tied (http://www.handprint.com/HP/WCL/color15.html) to the surface lightness.

Put alternately:

14. All ochres, browns and grays appear in surfaces have a lightness much less than the maximum lightness possible for the hue, creating the

unsaturated color zone.

The *chromaticity surface* is the physiological limit of monochromatic saturation at any luminance, and the *optimal color surface* is the theoretical limit of reflective material colorant saturation in surface colors all contain some component of WHITE reflectance, and BLUE VIOLET.

15. All nonfluorescing material surfaces are grayer (have a lower saturation and smaller lightness range) than either monochromatic lights or theoretically perfect physical colorants.

The *chromaticity surface* is the physiological limit of monochromatic saturation at any luminance, and the *optimal color surface* is the theoretical limit of reflective material colorant saturation in surface colors all contain some component of WHITE reflectance, and BLUE VIOLET.

16. Experienced as chromaticity, luminance variation is replicated as the color contrast between WHITE and BLUE VIOLET.

text here.

Definition of Key Terms. At the beginning, it seems right to ask: what exactly do we mean when we say two colors are harmonious or discordant? My answers are as follows:

a. Color relationships appear in the *visual effect* of color combinations they are not defined by abstract properties such as the proportions of "primary" colors that mix the colors, or by fixed geometrical patterns on a hue circle.

b. Color harmony occurs when an assortment of colors mimics a natural light environment, conforms to the scene illuminance, and clarifies the perception of form, pattern and representation for functional or esthetic ends.

c. Color discord occurs when two adjacent colors dull or shift the hue of the other color, or when a group of colors implies contradictory light qualities.

d. Color contrast occurs when the contiguous boundary between two color areas is enhanced or clarified.

e. Color fusion occurs when the boundary between adjacent color areas is subdued or disappears.

Principles of A Natural Harmony of Color. The fundamental principles of a natural color harmony are:

1. All color harmony, color discord, color contrast and color fusion effects are determined by (a) the *selection of colors,* (b) the *relative visual area and/or pattern* of the colors, (c) the *intensity and chromaticity* of the illumination, and (d) the *viewing context*.

2. All color combinations imply a particular kind of illumination.

increased average lightness (value) and/or increased lightness contrast imply higher illuminance (brighter light).
a limited range of hues or increased chroma within analogous hues implies a more chromatic illuminant (colored light).

3. Any pattern or color contrast appears more clearly in some color combinations than in others.

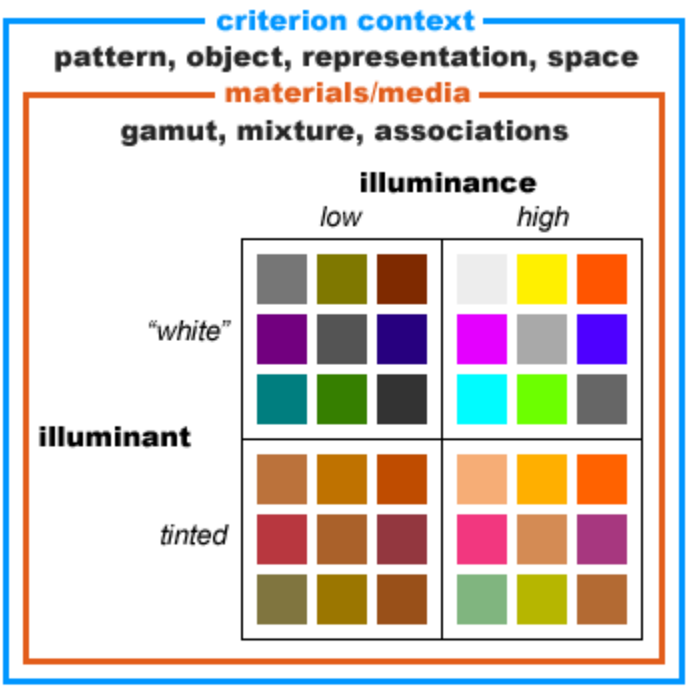
4. Any judgment of harmony or contrast requires a for the color design: pattern, object, representation, or environment.

The most important attribute of light is its intensity or illuminance (http://www.handprint.com/HP/WCL/color3.html#illuminance), and illuminance has consistent effects (http://www.handprint.com/HP/WCL/color3.html#brighttour) on the appearance of surface colors. The intensity of light reaching the eye from a surface area depends on the quantity of illumination, or *illuminance,* the relative proportion of light reflected by the surface, or *reflectance;* and the visual area of the surface in the field of view. All three combine to create luminance (http://www.handprint.com/HP/WCL/color3.html#luminance). When luminance is judged in relation to the average luminance in the environment the perception of *brightness* results; when the luminance is judged in relation to the maximum surface brightness the perception of *lightness* results. As illumination increases, the appearance of whites becomes brighter and less grayed, the contrast between darks and lights increases, and (for a "white" or balanced light source) the average saturation of all colors increases. This makes *white quality, value contrast* and *saturation contrast* the **three principal anchors** of a color design.

Brightness/lightness is the fundamental dimension of visual perception in general and color harmony or contrast in particular. All artistic media provide for a large variation in brightness/lightness; no artistic medium is limited to variations in hue/chroma only.

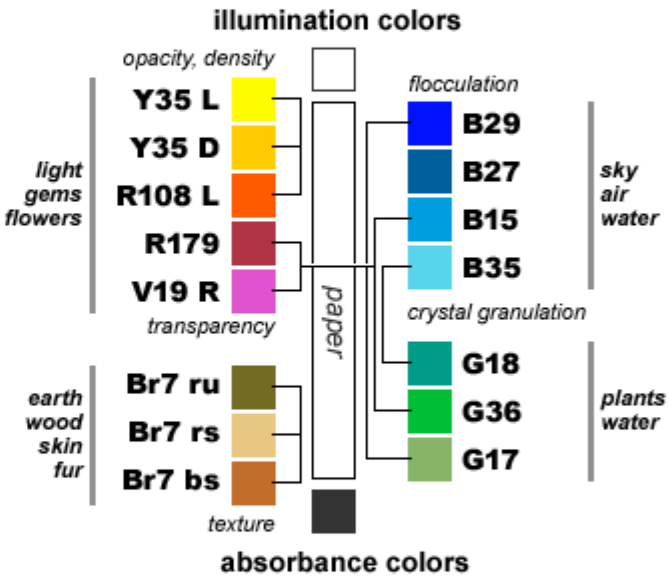
After illuminance, the next most important light attribute is its **tint or chromaticity**, defined as the illuminant (http://www.handprint.com/HP/WCL/color1.html#dayphases) or spectral power distribution of the light. The illuminant unifies all surface colors by mixing subtractively (http://www.handprint.com/HP/WCL/color10.html#surfaceshadow) with them. A balanced or "white" illuminant affects all colors equally, while a tinted or imbalanced illuminant increases the saturation of hues that are analogous with its tint and dulls the hues that are complementary to it; under a monochromatic or "pure color" light source all colors appear to be the same hue as the light, and colors vary only in lightness. So *average hue, hue diversity* and *saturation bias* are the **three secondary anchors** of a color design.

How we manipulate or select these nine color dimensions depends on the purpose of the color choices, which means we must always begin color design by stating or selecting a **criterion context**. So the artist always begins the color design process with a statement (clear idea) of the purpose of the color design and the context in which colors will be viewed as a pattern, an object, a representation or a space. The artist then studies the specific media available for the task (paints, inks, dyes, yarns, photographic emulsions, stained glasses, ceramic glazes, etc.) to understand the gamut and mixing behavior of the materials, and identify important color associations. And finally the artist chooses color combinations that **mimic the appearance of a hue selection under a certain light intensity and light tint**. The result is a harmonious, well contrasted color palette for a specific application, as shown in the schema (below).



a color harmony of light

I can't pretend this approach is definitive, but it is extremely reliable and easy to apply, because it groups the different aspects of color design into logically distinct layers. It also has the merit of avoiding the twin irrelevancies of traditional color theory "primary" colors (http://www.handprint.com/HP/WCL/color6.html) and abstract color geometry (http://www.handprint.com/HP/WCL/color13.html) (triangles, circles, etc). It can work just as effectively in textile design and representational ****, in the design of a vase or of an interior space.



pigment, color and material harmonies

New principles.

4. White and saturated red, yellow and blue are illumination colors; black, green and brown (darkened red or yellow) are absorptance colors.

 Any hue mixed with white (tint) mimics a radiating light; any hues mixed with black (shade) mimics an absorbing substance.

5. Colors are always perceived through *stereotypical color associations* or similarities between colors and distinctive objects or substances.

Finally, our color experience is continuous and lifelong. We come to associate colors with specific types of materials, viewing circumstances, and qualities of light. As artists, we also come to associate colors with specific pigments or hues of paint. This crystallizes the effects of illuminance and the illuminant as a selection of materials. The illustration (above) shows a representative selection of paints the one I prefer to use to evaluate a particular brand of paint. Each paint color has distinctive qualities of transparency, opacity, granulation or saturation. The color families are also strongly associated with certain real world materials or viewing situations, which often crystallize as compound color names (*sea green, sky blue, blood red, lemon yellow*). But overall, the colors divide into two groups: the whites, blues, yellows and reds that characterize the tint of natural light sources or the shadows they produce, and the greens, browns, grays and blacks that characterize the absorbance quality of plants, earth and stone that surround us in most environments. We also typically dislike colors if they remind us of undesirable materials, such as excrement, pus, slime or dirt. So *media choices, viewing context* and *natural hue associations* constitute the **three tertiary anchors** of a color design.

Illuminant and Local Color. One common way color unity arises is through the dominating effect of a colored light or illuminant, which tints all the local colors (object colors) in the image. Let's look at how that happens.

the color circle in "colorless" white light

Take as the starting point a "pure" hue circle, with equally saturated hues around the circumference. This is the wheel as it would appear in "colorless" white light, where all wavelengths are present in equal amounts.

same hues illuminated by middle blue light

We simulate the effect of a colored illuminant by placing over the hue circle a middle blue filter (the same color as the circled color point, 8). This filter changes the colors in the same way that a strong, blue colored light would change the apparent colors of objects.

At first glance, we seem to see the hue circle unchanged behind a transparent blue screen, but in fact the color of almost all the hue markers has been shifted substantially by the blue color.

shifts in the colors caused by middle blue light

We can show this by restoring the white background, but leaving the hue of the color chips the same. These are plotted on a color map, under "white" light again, but with the markers shifted to show their apparent hue and saturation behind the blue filter. As you see, the colors have been shifted closer together by the blue hue they have in common.

The *basic pattern* of these color shifts is the same no matter what hue of light we might choose, and it's worth memorizing it specifically:

Colors the same hue as the light increase in lightness. There is no change in the hue of a middle blue object viewed through a middle blue filter, but it will generally appear lighter valued. Neutrals (grays and white) become tinted with the color of the light.

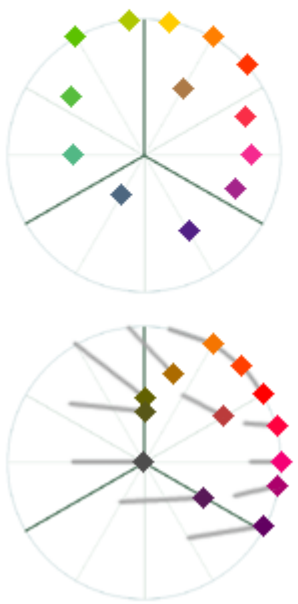
All hues shift toward the color of the light. This is because each color has been mixed with the middle blue, to create a new hue that is somewhere on the mixing line between the original color and middle blue.

The **color shifts are greatest for far triadic colors**, the colors that are between the two triadic colors (12 and 4) opposite the color of the light; these are colors analogous to the complementary color of the light (deep yellow) which loses saturation the most (is shifted most toward the center of the hue circle). This shift affects the reds, oranges and light yellows as well.

The **apparent gray is an unsaturated complementary color of the light**, in this example an unsaturated tone of the deep yellow around color point 2.

As a result of these changes in hue and saturation, **overall color variety is reduced**, though lightness contrasts may increase. The total color space is smaller, and some colors have disappeared entirely there is no longer any red, orange or yellow visible in the colors.

The size of this color shift depends less on the strength of the illuminant than on the intensity of its color. A common example is the shift in colors that occurs around sunrise or sunset, when the sun's light is weakest but also strongly tinted.



shifts in hues from sunset to dusk

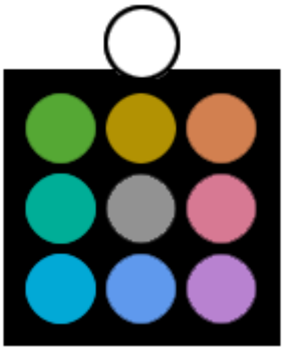
The diagram shows the shift in colors that occurs when a moderate deep yellow tint is placed over a hue circle, and again when the illuminant is a stronger red orange. (Remember, you can identify the color of the illuminant by the direction of the shift of the neutral tones.) As you see, the stronger light creates a tighter circle of hues, and a closer spacing among the colors on the warm side of the hue circle.

This leads to a few new principles:

6. *Analogous colors* are the surface colors that similarly increase in chroma and/or lightness, or become more alike in hue, under a strongly tinted or monochromatic illuminant.

7. *Complementary analogous colors* are the surface colors that similarly darken or decrease in chroma under a strongly tinted or monochromatic illuminant.

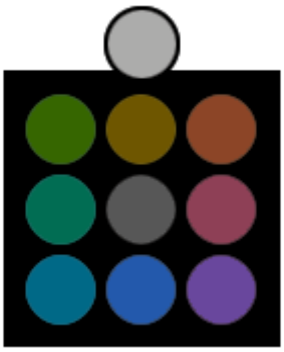
Natural vs. Traditional Hue Harmonies. Let's now use these principles to derive the .



a nuance matrix

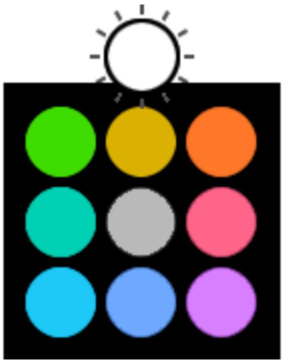
color samples from the hue circle at matching chroma and lightness, with a gray sample of matching lightness

Our method of illustration starts with a **nuance matrix**. This is a representative sample of hues from around the hue circle, all at equal chroma (or saturation) and lightness. Above the matrix is a color sample area used to display the luminance and chromaticity of the light source. Ideally, a reflection or image of the light source would be displayed here, but as these illustrations are presented in surface colors we have to make do with grays and tints of white.



the nuance matrix under dim light

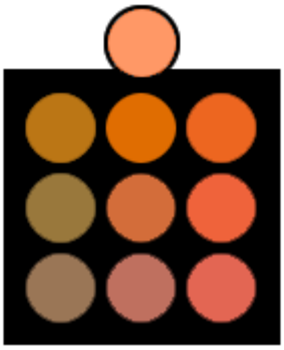
Under dim illumination the lightness and chroma of the nuance matrix contracts, but there is little change in the relative difference among the colors.



the nuance matrix under bright light

corresponding to the triadic or quadratic color harmonies

Under a very bright illuminant the chroma and lightness of all colors expands, the color variety appears greater. This corresponds to the and color harmonies, which differ in the secondary gamut or hue sampling imposed by the surface colors of the nuance matrix.

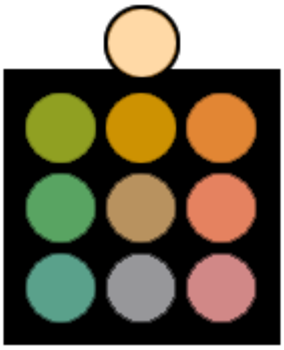


the nuance matrix under a strong chromatic illuminant

corresponding to the monochromatic color harmony

Next, we can view the nuance matrix under a strongly chromatic or monochromatic illuminant. This reduces all the color samples to variations on a single hue, the hue of the illuminant, corresponding to the color harmony.

Here the relative attractiveness of the harmony depends on the familiarity of the illuminant. Red, yellow or blue monochromatic harmonies, which resemble the effects of natural sunlight or skylight across different daylight phases, are much more attractive and useful that magenta, purple or green monochromatic harmonies, as these are illuminant colors we do not encounter in natural illumination.



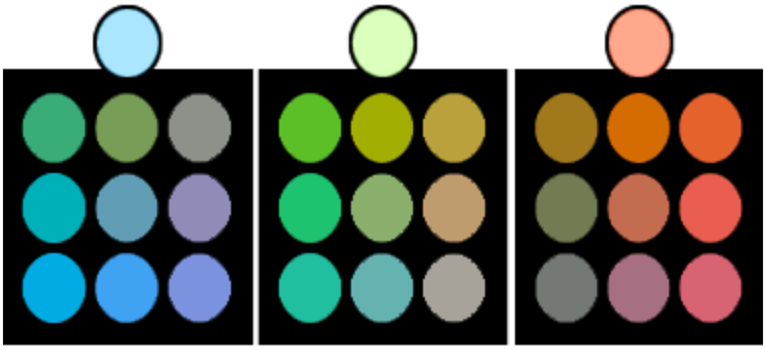
the nuance matrix under a weak chromatic illuminant

corresponding to an analogous color harmony in which one hue of the nuance matrix has been neutralized to gray

As we reduce the chromatic intensity of the illuminant, for example by mixing a monochromatic illuminant with increasing amounts of "white" light, we relax the constricted color range of the monochromatic color harmony and expand into the color harmony.

The process of mixing "white" and chromatic illuminants leaves open the proportional quantities of the two that we use, and this translates into a wide range of analogous color harmonies. This corresponds to the common difficulty in defining precisely what an analogous color harmony represents: precise definition is not possible. Instead we have a range of harmonies in which the proportion of the chromatic illuminant in the light mixture may be small or large.

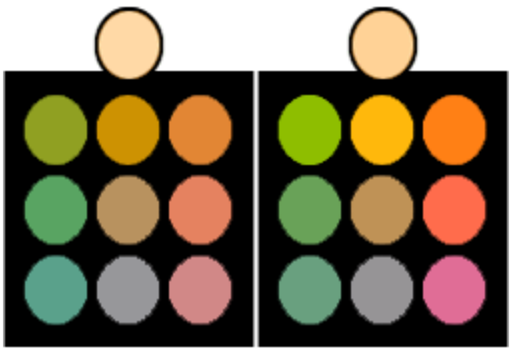
However, I can suggest a reasonable anchor point: using a white/chromatic mixture in which the chromatic component is just strong enough to neutralize one hue of the nuance matrix.



variety in "analogous" color harmonies

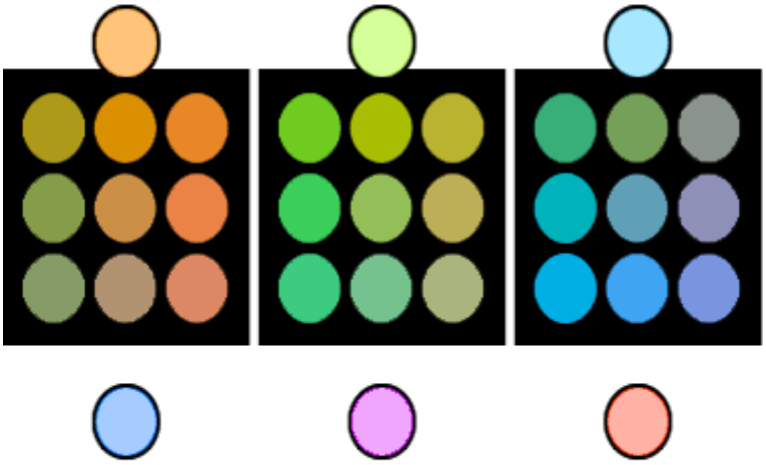
An interesting insight provided by the natural color theory is that "analogous" color schemes are not as consistent as we are taught in traditional color theory. In the examples above, the "red" analogous scheme (far right) contains a much more restricted color range than the "yellow green" scheme (center).

We also discover that the analogous color harmony may even contain a complementary color contrast, which we see in the green and purple samples adjacent to the gray sample in the "cyan" scheme (far left), or the dull orange and turquoise samples adjacent to the gray sample in the "yellow green" scheme.



effect of increased chroma on the nuance matrix the visual boundaries of an analogous color harmony are ambiguous

Increasing the chroma in the nuance matrix requires an increased chromaticity in the illuminant to neutralize the complementary hue of surface color. This also has the effect of breaking out the boundaries of the analogous palette even further. To appear in natural light situations, then, an analogous color scheme implies strongly saturated surface colors with a strongly chromatic illuminant, or relatively dull surface colors with a weakly chromatic illuminant. That is, there is a harmony or balance between the chromatic intensity of the surfaces and the light source.



nuance matrices with complementary light sources

corresponding to split complementary color harmonies

To produce the color harmony, we can no longer rely on a single chromatic illuminant, because the surface color withthe complementary hue is by definition the hue reduced to gray by the light source. The only way to create the complementary hue is with a second light source.

The strong effect of the split complementary harmony derives from the fact that one of the complementary hues must be a second light source, typically seen in a way that restricts its cast over surfaces. Common examples are the illuminated windows of a house seen around twilight, a red signal light seen on a dark day, or a blue signal light seen at sunset.

nuance matrix with strong chromatic light source and complementary light source

corresponding to the complementary color harmony

The irreal effect of a color harmony is at its peak in the color harmony. To observe this in natural illumination we must have two strongly chromatic light sources of complementary hue, at least one of which is strong enough to produce a monochromatic palette in the nuance matrix, and each casting light from a different direction, so that different sides of the same object are illuminated by each light.

This contrast was traditionally observed in the classic demonstration of visual complementary colors, using shadows cast from two different light sources; but in those demonstrations the second "light source" is the simultaneous contrast mechanism of color vision, which produces a beautifully muted color variety.

It is exceedingly rare and unnatural to find the contrasting colors produced on the illuminated surfaces of objects; in fact the effect is characteristic of certain kinds of stage lighting. Thus, the natural color theory shows that the complementary color scheme, which has traditionally be lauded in "color theory" texts as the most effective color contrast, turns out also to produce the most unnatural and irreal effect in representation.

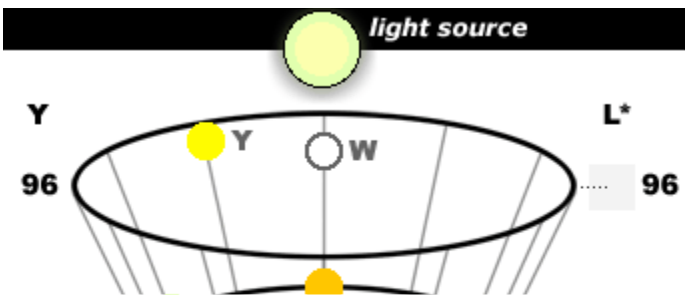
Color Relationships in Perception. The intensity of light reflected from surfaces has a nonlinear relationship to chromatic and lightness contrast, as appears in a side view of the cone excitation space (http://www.handprint.com/HP/WCL/color2.html#excitationspace). One intuitive way to divide this space is to start with the reflectance of a pure white surface, which is nominally **Y** = 96, then take half steps of reflectance from there (**Y** = 48, 24, 12, 6, 3 and 1.5). These produce lightness boundaries at approximately **CIE L*** = 96, 75, 55, 40, 30, 20 and 13. (These divisions are arbitrary and other divisions are possible, but they are easy to remember, track important color changes, and anchor lightness in the luminance from the colored surfaces.)

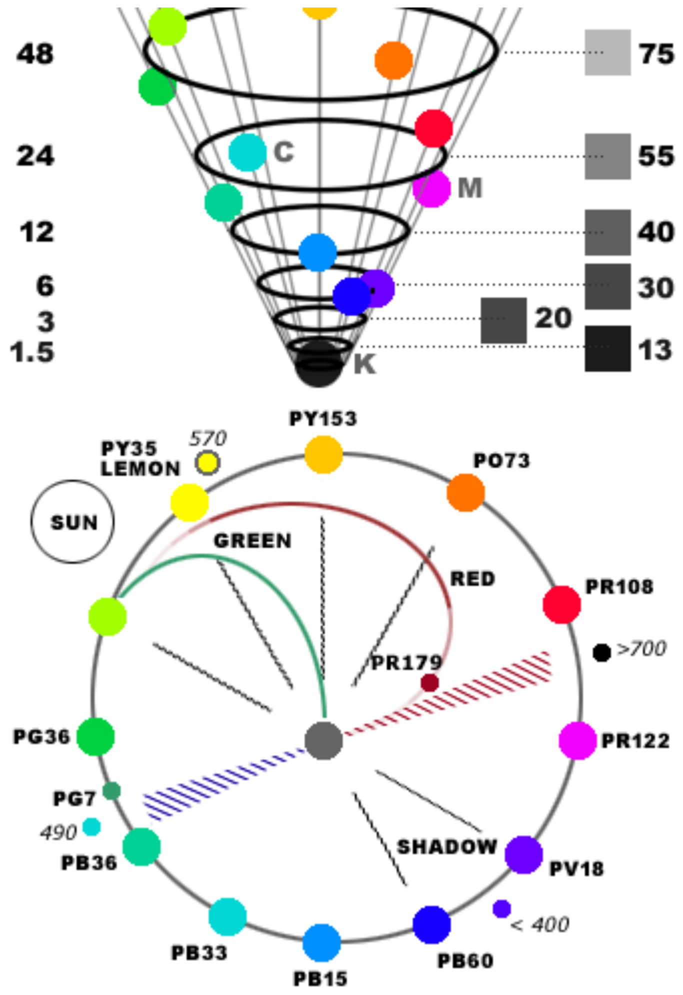
1. The focal color is in all other colors, therefore the focal color is the illuminant.

A color harmony is determined by the focal color. 2. FC = R I_C

2. FC = R 0 [I_C= chromatic adaptation]

When the hue circle of tertiary hues is scaled across these seven lightness levels, scaled so that the area within each hue circle is equal to the luminance of its colors, the location of hues at maximum chroma forms an oblique pattern within a cone (diagram, below).





the color harmony of light

The effect of these

bright colors (**Y** = 96 to 48, **L*** = 96 to 75): these colors have three important characteristics: (1) in objects, they appear in all refraction cues (iridescence, rainbows, gems), in darkly colored surfaces oversaturated with light, and in saturated surfaces viewed through a veil or fog; (2) in pigments, they are produced by mixtures of pure pigment with white; and (3) they produce strong chroma only across the hues YO, Y and GY; all other hues appear whitened yellow must be darkened or whitened in any "pastel" color scheme, otherwise its high chroma will make it "pop" against other whitened hues.

light colors (**Y** = 48 to 24, **L*** = 75 to 55): these colors characterize material surfaces of relatively high reflectance: (1) bright colors (YO to GY) dull to ochre or green gold, (2) new bright colors appear in the range RO to R; (3) the matching colors G and BG have a similar lightness, but lower saturation; (4) the hues V and RB still appear whitened.

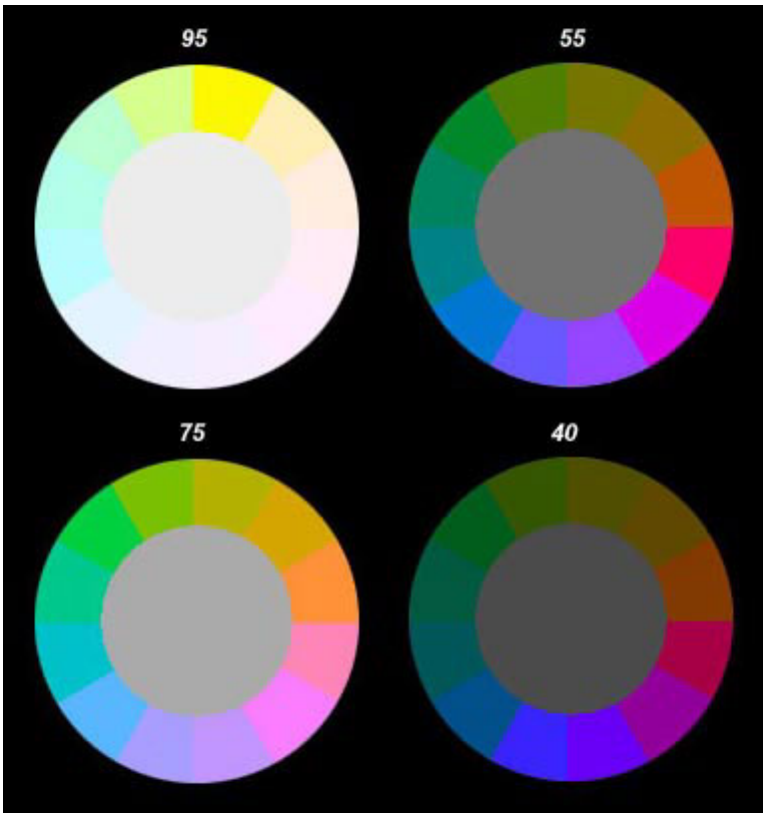
dark colors (**Y** = 24 to 12, **L*** = 55 to 40): these colors represent surfaces of average to low reflectance: (1) the light colors RO to R darken into brown or maroon, and the bright colors YO to GY darken to dark green or greenish gray, (2) the last bright colors appear at M and C, (3) all blues and greens are brightest in this range.

shadow colors (**Y** = 12 to 6, **L*** = 40 to 30): these colors (1) present shining chroma only in RB and V. As this is never the color of a natural illuminant, RB and V do not appear highly saturated.

black colors (**Y** = L* = around 20.) In this lightness range, hue contrasts and chromatic luminance disappear, though a warm/cool potency remains.

The hue circle below the lightness cone shows the major landmarks in the color space: the red boundary and green boundary in the unsaturated color zones (http://www.handprint.com/HP/WCL/color12.html#satmap), the long wavelength *dark horizon* in spectrum reds at 700 nm, the typical location of the unique yellow balance point at 575 nm, the secondary *dark zone* at around 490 nm (due to the bimodal sensitivity (http://www.handprint.com/HP/WCL/color1.html#dipict) of chromatic discrimination), and the short wavelength *dark horizon* at around 400 nm. The hue circle also locates the approximate chromaticity of noon sunlight (sun), and of noon skylight (shadow).

There is a characteristic lightness we associate with the "ideal" example of a specific hue or unsaturated color. color appearance can be judged in the four hue circles below, which show the tertiary hues at the bright, light, shadow and dark color boundaries.



hue and chroma at four lightness levels

As displayed in the artist's value wheel (http://www.handprint.com/HP/WCL/vwheel.html), different pigments correspond to these four lightness categories. The daytime sky ranges in apparent lightness approximately between 55 to 75, depending on atmosphere, season and altitude of the sun.

Five Palette Types. Look at how these ideas relate to traditional color harmony concepts.

1. The Illuminance Palette. This is the traditional value design palette (http://www.handprint.com/HP/WCL/palette4a.html) of etchings. The palette signals luminance contrast (overall reflectance) only, typically with no chromaticity information added.

The image itself may be chromatic, as for example in sepia prints, but the chromatic content is not varied in a way corresponding to either local colors or illumination effects.

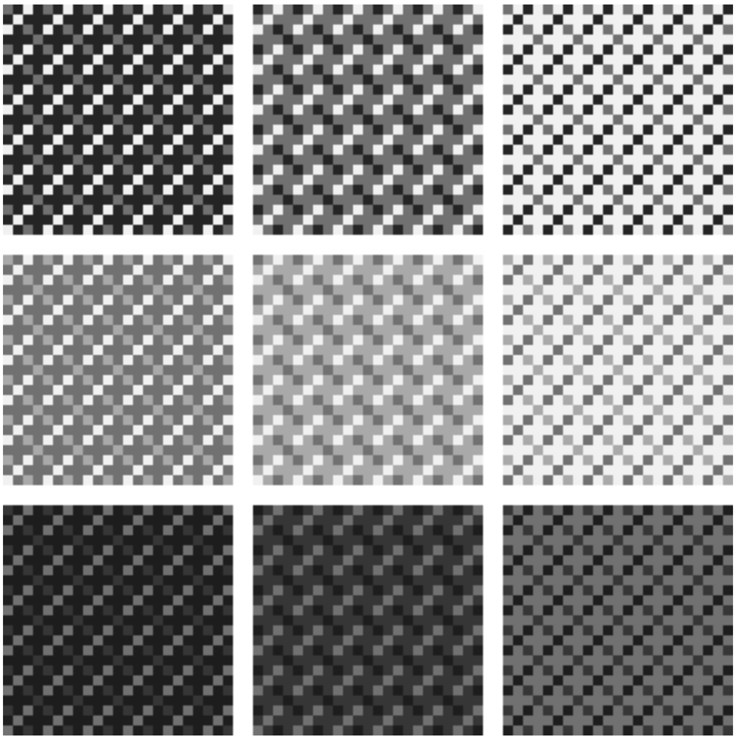
There have been a few modern attempts to use chromaticity as a luminance symbol. This practice can be traced back to medieval painters, who used blues and browns for darks, and yellows or whites for lights, building on the Aristotelian color theory (http://www.handprint.com/HP/WCL/color6.html#ancient) of ancient times. It is therefore a trait of color primitivism or color symbolism, although the radiant images made with polarizing filters show it can be produced in the real world.

luminance palette in london ****s of andré derain

For a short period in his career the French fauvist painter André Derain experimented with a luminance palette, and the use of the method is signaled by (for example) the trees that are red rather than green, or a sky that is green (or red) rather than blue. Note that he has to omit the use of yellow greens in order to allow the use of orange, and uses middle blues as a tinting color in the darks. He also makes red lighter than green (as for example in the sky) because of the red's greater saturation.

The Australian painter Wayne Roberts proposed a luminance palette based on the photon energy (http://www.wroberts.com.au/html/about_painting_light.html) of light wavelengths, which makes red the "darkest" (lowest energy) color and violet the "lightest" (highest energy) color. Although this produces a systematic mapping of all hues into any image, it visually destroys both the value structure and the virtual illumination. Derain, by using hues in their characteristic lightness as paints, retains both a clear value structure and a feel for the landscape illumination, as a luminance palette should.

2. The Monochromatic Palette. This is the palette defined by a monochromatic illuminant without simultaneous contrast. It is equivalent to the color scheme, which often expresses the effects of a strong illumination.



lightness contrasts

textile patterns of (top) high light, high contrast (**L*** = **96, 55, 20**); (middle) high light, low contrast (**L*** = **96, 75, 55**); (bottom) low light, low contrast (**L*** = **55, 30, 20**)

Brilliance of whites

Gray point.

Saturation.

Light Chromaticity. The tint or color of the illumination, or *illuminant*.

White point (color balance)

Saturation range

Max. vs. Min saturation by hue

"Black span"

Dark, cool hues shift the room shadows in their direction; a bright warm accent appears as a common light in room and ****.

Surface Adaptation. Gradation, figure/ground, edge clarity.

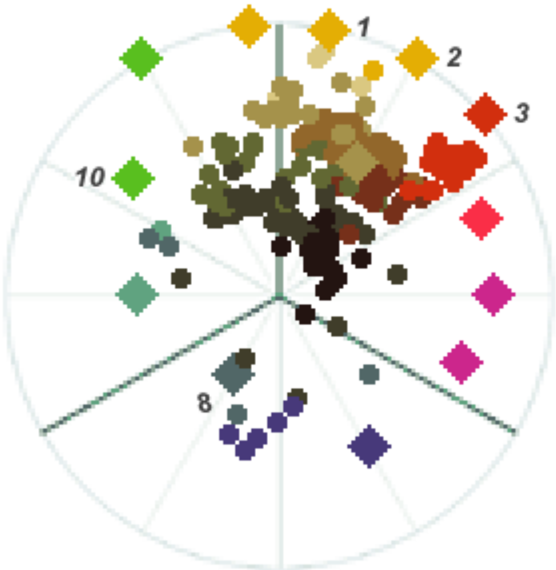
Materials & Medium. The principles defined by the natural color harmony are always subject to the limitations of the specific media (paints, dyes, phosphors, lights) used to create the full range of colors.

Many attractive palettes have been handed down from ancient times (Egyptian color palette) that are entirely defined by natural pigments. These often fit within the nuance space, as they are generally dull pigments.

Gauguin, Again.

Bright, warm hues match the light in the room; dark areas are pushed away from the light.

In general, as we move from a tetradic or triadic color scheme through the split complementary, complementary, analogous and monochromatic color schemes, we are basically imitating the effects of increasingly chromatic illuminants.



sunset colors combined with the gauguin color map

If we refer back to the Gauguin palette map (top), and lay the moderately shifted colors of the deep yellow illuminant on top, we see how neatly Gauguin's choice of hues has imitated a deep yellow light. The shifted neutral color chip is centered over the large yellow ochre cluster in Gauguin's palette; the accenting blues and greens are at the saturated limits on the far side of the color space.

Gauguin has increased the analogous effect by eliminating all colors on the magenta and violet sides of the color space there is a large empty area in the lower left part of the circle of shifted colors. Of course, this helps to increase the intensity of the warm colors, and in particular enhances the impact of the scarlet hues.

The two warm palette colors we had identified in his palette scarlet and middle yellow bracket the color point 2 on the wheel, which is the general direction of the color shifts.

the gauguin color harmony and illuminant shifted palette

This analysis suggests that the impact of Gauguin's palette arises in part because it imitates, with careful limitations and accents, the overall pattern of colors that would arise from natural shifts caused by a warm yellow light.

The general plan seems to be more like a lopsided tetradic harmony (1-3-8-10), shifted by the illuminant to an even more lopsided area of the color space.

Of course, much of the beauty of the **** arises because these color effects are not entirely realistic, but adopted as a point of departure for color that is partly symbolic. But that is enough to suggest a general color design method (http://www.handprint.com/HP/WCL/palette5.html) that you can use to work out the color scheme of a ****.

ruskin's last word

I'd like to conclude this long page, which has wrestled with many ideas inherited from "color theory", with a few words from John Ruskin (http://www.handprint.com/HP/WCL/artist09.html), a remarkably gifted artist and art critic.

In his classic tutorial The Elements of Drawing (http://www.handprint.com/HP/WCL/book4.html#ruskin), Ruskin spends some time talking about the problems of color harmony. Here are his thoughts:

There is no better test of your color tones [value design] being good, than your having made the white in your picture precious, and the black conspicuous....

Nearly all good [mixed] colors are odd *colors. You shall look at a hue in a good painter's work ten minutes before you know what to call it.... If you try to copy it you will find always your color is too warm or too cold.*

As to the choice and harmony of colors in general, if you cannot choose and harmonize them by instinct, you will never do it at all. If you need examples of utterly harsh and horrible color, you may find plenty given in treatises on coloring, to illustrate the laws of harmony.

If you want to color beautifully, color as best pleases yourself at quiet times, *not so as to catch the eye, nor look as if it were clever or difficult to color in that way, but so that the color may be pleasant to you when you are happy or thoughtful.*

If ever any scientific person tells you that two colors are 'discordant,' make a note of the two colors, and put them together whenever you can.

If you enjoy [colors], depend upon it you will paint them to a certain point right: or, at least, if you do not enjoy them, you are certain to paint them wrong. If color does not give you intense pleasure, let it alone; depend upon it, you are only tormenting the eyes and senses of people who feel color.

Your power of coloring depends much on your state of health and right balance of mind: when you are fatigued or ill you will not see colors well, and when you are ill-tempered you will not choose them well.

Only observe always this, that the less *color you do the work with, the better it will always be*.

My last word is this: take the ideas on this page as guidelines for exploring color rather than as rules for using color. Try the various color schemes for yourself; vary the number of colors you use; try all the schemes with unsaturated colors only. Experiment with altering the schemes to capture the effects of light or mood.

Always do everything to the best of your skill, and in this spirit "so that the color may be pleasant to you when you are happy or thoughtful" and your color harmonies will be beautiful without any theory.

Related Material

traditional hue harmonies

Let's begin with the color harmony patterns traditionally taught in visual design classes and art texts (links, right). These provide a standardized vocabulary for identifying color combinations or palette designs (http://www.handprint.com/HP/WCL/paletfs.html).

These are not really *color* harmonies, because they are defined only in terms of **hue relationships** around the hue circle *red and yellow are analogous colors, red is the complement of green,* and so on. The colormaking attributes (http://www.handprint.com/HP/WCL/color3.html#colormaking) of chroma and lightness (tonal value) are not considered. I call these **hue harmonies** to distinguish them from that include hue, lightness and chroma.

Traditional hue harmonies are defined on the circumference of the hue circle, as the most saturated colors (light valued yellow, dark valued violet, mid valued red, and so on); derivative or "broken" colors unsaturated tones, tints and dark valued shades are equated with the saturated hue. In this way the hue harmony can be adapted to almost any specific **color scheme** or selection of paints for a palette.

Most color designs are dominated by a single hue, the **key color**, around which all the other colors are organized. This can be a **mother color** if most or all other colors are mixed with it. Otherwise the key color represents the overall color impact of colorant mixtures. Once you've identified the key color, then the color harmony emerges from the relationship of the other colors to it.

Monochromatic. The simplest color scheme is made of a single hue that varies only in saturation and value. This is the **monochromatic** color harmony. It corresponds to Chevreul's : a single colorant mixed with white and/or black.

To create a monochromatic palette, (1) choose a key color at the edge of the hue circle, and (2) mix this color with white and/or black in any proportions. Or: (1) choose a dark, warm or cool, near neutral color, and (2) choose a paper that is also lightly tinted either warm or cool.

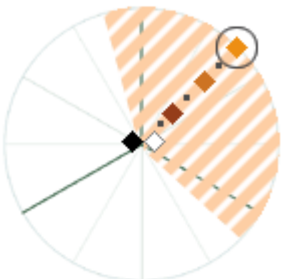
An alternative method is to supplement the saturated key color with a near neutral (unsaturated) color of approximately the same hue: indanthrone blue with ultramarine blue, or burnt sienna with cadmium scarlet.

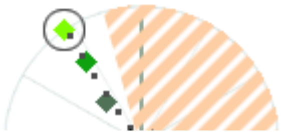
The monochromatic scheme puts the emphasis directly on the value structure the gradations in light and dark. However the artist can vary how much hue enters into the picture as ornament or a description of the illumination. To minimize hue completely, artists choose a black or neutral paint, such as sepia or neutral tint, as the single color; this is the value design (http://www.handprint.com/HP/WCL/palette4a.html) palette. By diluting this one paint the artist can achieve a full value range, with no variation in hue.

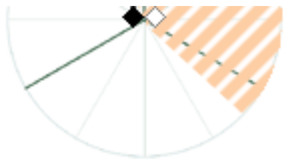
There are three principal variations on this hue harmony, exemplified by light gradations, earth gradations and floral gradations. A sepia ink wash drawing is a classic monochromatic palette that in washes leans slightly into warm, light values. Drawings made with red, black and white chalk exemplify earth mixtures and are commonly used for portrait and figure nude drawings. Greens on grays create lovely floral designs. Monochromatic blues against whites are a classic color scheme in both Asian and European ceramics.

Hue can be brought in very subtly by diluting a near neutral color such as burnt umber or indigo. Some indigos (http://www.handprint.com/HP/WCL/waterb.html#indigo), for example, will dilute out to silvery or pale greenish tints, giving a painting a beautifully subtle color range.

For greater hue emphasis, use greens or blues that hold their hue across all shades and tones. The final variation is a warm key color, from yellow to magenta and including violet. These colors seem qualitatively to change hue across the unsaturated color zones (http://www.handprint.com/HP/WCL/color12.html#unzones), giving an analogous color effect even though only one hue is present. Orange will shift to brown or pink, yellow to umber or green, and violet to shift blue violet or red violet, depending on the mixture lightness and chroma.







(http://www.handprint.com/HP/WCL/colormap.html)

monochromatic color harmonies

the key color is circled;
area of "warm" hues is shaded

Analogous. The next color harmony consists of neighbor hues along the circumference of the hue circle.

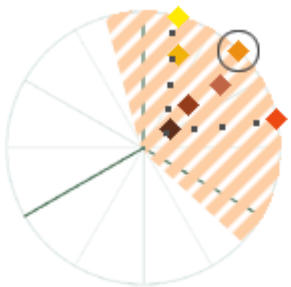
To create an analogous palette, (1) choose a key color on the hue circle, then (2) choose two hues on either side of the key color within the same hue family of RED, YELLOW, GREEN, BLUE, VIOLET, WARM or COOL. You are permitted to use any color mixed from these colors and/or with white, black or a dark neutral.

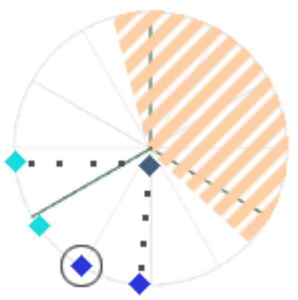
There is no fixed rule for the range of hues permitted in an analogous color scheme; depending on the choice of key color, the range can vary from 45° to 90° on the visual hue circle. The key color is usually near the center of the hue range, but can be at either end.

However a good rule of thumb is that analogous color schemes only include colors in which the key color is the dominant hue. If the key color is orange, analogous hues range from orange yellow to orange red (excluding yellow and red); if the key color is blue, the hues can range from blue green to blue violet (excluding green and violet). These schemes never include both warm and cool colors (http://www.handprint.com/HP/WCL/color12.html#warmcool), as these are color opposites rather than color siblings.

To preserve color unity, colorant mixtures in an analogous palette should be grayed with a single complementary color, and mixtures that take the color out of family for example, yellows that are dulled until they appear dark green must usually be rejected.

Analogous colors produce a strongly unified effect. Subtly handled, they suggest the natural color unity we encounter in certain motifs (the greens of a lily pond), environments (the reds and browns of a desert) or light (the blue of twilight). These unities often signal a synergy between materials and illumination the greenery of a dense forest excludes warm light, for example. Used too assertively, especially as strongly saturated colors, analogous schemes can have a claustrophobic or constraining effect, and can clash with color schemes around them.





analogous color harmonies

the key color is circled

Complementary. Probably the single most important color relationship in traditional color theory is defined by **complementary colors**, two hues that are roughly opposite each other on the hue circle.

To create a complementary color harmony, (1) choose a key color at the edge of the hue circle, then (2) choose a color opposite to it on the hue circle. You are permitted to include any color mixture along a line between these two, and to use any mixture of those colors with white, black or a dark neutral.

Complementary colors are traditionally defined as two colorants that mix a "perfect neutral" black or gray in subtractive mixtures, white in additive mixtures. These two methods yield different definitions of complementary hues. Insurmountable practical problems (http://www.handprint.com/HP/WCL/color16.html#mixprobs), and the obvious point that viewers only see colorant mixtures, not the ingredients in the colorant mixtures, indicate that a visual hue circle (http://www.handprint.com/HP/WCL/vismixmap.html#munsell) be preferred to define complementary color relationships.

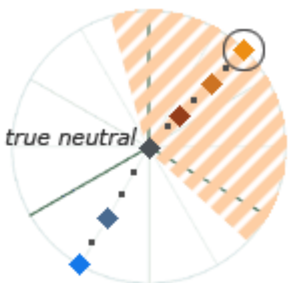
But this proves awkward when complementary colors are chosen so that they can be mixed to neutralize or darken each other, the method commonly recommended to painters. Visual complements along the **a+/a** (red/green) opponent dimension (http://www.handprint.com/HP/WCL/color18a.html#modernhuegeometry) will do this handily, but visual complements along the **b+/b** (yellow/violet) opponent dimension produce greens or browns. I suggest you always design in terms of the visual complements, then use whatever colorant mixtures produce the effects you want.

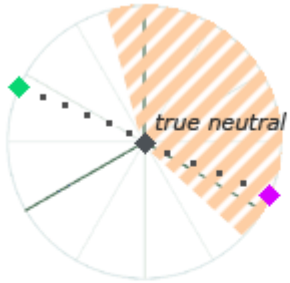
Traditional color wheel geometry dictates that complementary colors are either a "primary" color and the secondary color (http://www.handprint.com/HP/WCL/color13.html#secondary) opposite, or two tertiary colors (http://www.handprint.com/HP/WCL/color13.html#tertiary). This is a restrictive and obsolete way to approach color design. In fact, the difference between complementary pairs defined on visual and mixing hue circles (http://www.handprint.com/HP/WCL/color16.html#complement) usually lets the artist choose a fairly wide range of complementary matches for any key color.

The presence or lack of a near gray in the complement mixtures affects the overall color range: if a near gray is lacking, the palette resembles a triadic scheme with a very unsaturated third "primary" (e.g., brown between yellow and violet, or green between yellow and blue). This effect is suppressed when a dark neutral is used to produce unsaturated and neutral mixtures. When the complements do mix to a dark neutral (such as dioxazine violet and sap green), the dark neutral permits strong variation in tonal values.

A subsidiary design issue is the relative dominance of either complement as the key color of the scheme. Normally the key color will occupy the greater space in the image, define the dominant pattern, appear in the wider range of mixed colors, or appear in saturated or pure form. The range of value and chroma across all colors affects their weight in the total composition, and these can be used to adjust and vary the relative weight of the colors.

Some artists add colors along the mixing line between complements to extend the value range without expanding the range of hues. The complementary harmony of quinacridone rose (PV19 (http://www.handprint.com/HP/WCL/waterc.html#PV19R)) and viridian (PG18 (http://www.handprint.com/HP/WCL/waterg.html#PG18)) is not capable of rich dark neutrals, but when umber violet and cobalt green dark are added, near black tones and unsaturated tints can be mixed without adding a new hue to the scheme.





complementary color harmony

(orange and blue, or magenta and green); the key color is circled

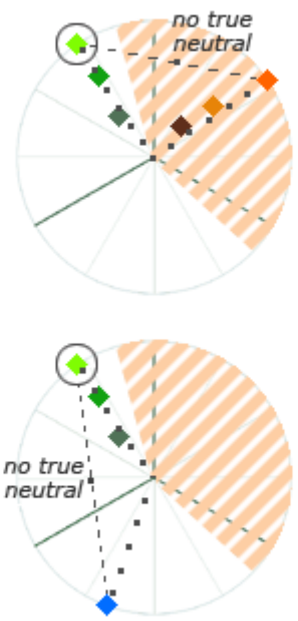
Off Complementary. The force of tradition, with its emphasis on either triadic "primary" color relationships or dyadic complementary color relationships, has orphaned what I believe is an essential color harmony: **off complementary colors**. These are two hues separated by roughly a 120° angle (one third of the circumference) on the hue circle.

To create an off complementary color harmony, (1) choose a key color at the edge of the hue circle, then (2) choose a color approximately one third of the circumference in either direction around the hue circle. You are permitted to choose any colors mixed from these two, along a line between these two, and any mixture of those colors with white, black or a dark neutral.

Off complementary combinations have the punch of a strong hue contrast, but without the clash of hue antagonists and the dulling effect of strongly neutralizing mixtures. Indeed, an excellent method for adjusting your final choice of two hues is by examining the mixtures they produce.

Off complementary relationships have sometimes been treated as complementary relationships in traditional color theory yellow green is just a GREEN, and red orange is just a RED, for example but this obscures the actual complementary relationship (red and blue green) in order to preserve an antiquated color dogma.

In terms of the relative dominance of the two hues, or the role played by the darker and less saturated mixtures, off complementary schemes can be handled like complementary color schemes. The artist should pay attention in particular to the many examples of off complementary color relationships in organic color the orange and green of a ripe mango is my favorite, and there are other examples in the green to orange of fall leaves, the blue and green of grass and sky, the violet and orange of a cloudy sunset. Off complementary contrasts are among the most spectacular and enchanting displays of nature.



off complementary color harmony

(yellow green and blue, or yellow green and orange); the key color is circled

Split Complementary. One of the most popular color schemes for expressive color effects, the **split complementary** color harmony simply adds analogous hues to one side of a complementary color pair.

To create a split complementary palette, (1) choose a key color at the edge of the hue *circle, (2) choose a color opposite to it on the hue circle, then (3) choose analogous colors on either side of the key color, and (4) choose any unsaturated colors within the color area spanned by the saturated colors. You are permitted to use any mixture of these colors among themselves and with white, black or a dark neutral.*

The key color is bracketed by the analogous colors ("split" complements); the opposite complement is the **accent color** to the key color. This puts the emphasis on the key color in two ways: by accenting it with its complementary color, and by extending its color resonance through analogous hues.

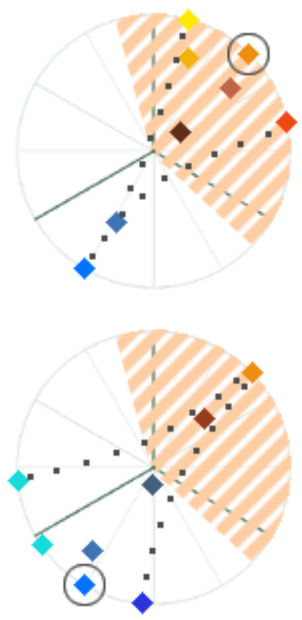
Because are usually not centered on the "primary" yellow or magenta colors, split complementary harmonies with a warm key color are usually aligned roughly along the warm/cool color contrast (http://www.handprint.com/HP/WCL/color12.html#warmcool); the accent color is usually between a blue green to reddish blue.

If the key color is a cool color, the analogous grouping can range across a wider span, from warm greens through warm violets, and the the accent complement can be any warm color from red violet to light yellow.

The variety of pure colors and color mixtures in a split complementary palette greatly expands the richness of the palette without obscuring the emphasis on the key color. Usually a complete range of neutrals can be mixed with the complementary pair. The key color and its analogous hues can be used broadly in unsaturated or darkened mixtures, and the accent hue applied as small, saturated color areas: the key and analogous colors form the background neutrals that create a brilliant, jewellike effect in the accent color.

In a natural setting, a common reason why a range of unsaturated analogous hues can include a strongly saturated complementary hue is because the complementary hue is a source of illumination in darkness a illuminated window in a house, appearing as a yellow accent surrounded by a dark violet and ultramarine evening. Another reason is that shadow colors are typically the complementary hue (http://www.handprint.com/HP/WCL/color10.html#shadows) of the dominant illumination; if the key color analogous hues represent surfaces tinted by strong light, then the complementary accent color will be the tint given to shadows by the eye.

Some split complementary palettes expand the range of analogous colors, usually forcing the accent complement a little to one side or the other of the key color (see the figure above, at right). If pushed too far, this transforms the split complementary scheme into a triadic scheme suggesting there is not a sharp distinction between the two.



split complementary color harmony

the key color is circled; all colors between the dotted lines are mixtures

Triadic. Along with complementary colors, the **triadic** color harmony has been extremely important in traditional color theory. It originally consisted of the three "primary" colors red, yellow and blue in this form it is the basis for wide range of palette designs (http://www.handprint.com/HP/WCL/palette4c.html). In fact, triadic hue schemes can be developed on any key color around the hue circle.

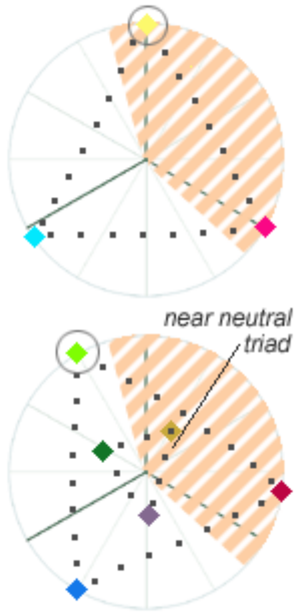
To create a triadic palette, (1) choose any three colors in the categories RED (including magenta), YELLOW (including green gold) and BLUE (including cyan) [the subtractive primary colors]; or any three colors in the categories RED (including red orange), GREEN and VIOLET (including blue violet) [the additive primary colors]; or any three hues separated by about 120° on the hue circle. There is no key color necessarily, and the hue spacing and saturation limits of the colors are flexible. You can use any mixture of these three "primaries" with themselves and with white, black or a dark neutral.

Because the three subtractive primaries can mix a very wide range of hues, any other colorants can be included in the triadic scheme, provided they lie within the gamut of the three primary colorants.

A triadic palette also does not have to consist of saturated colors. The righthand example shows a **near neutral triad** of raw sienna, hooker's green and indanthrone blue. (The Velázquez palette (http://www.handprint.com/HP/WCL/palette4b.html), with indanthrone blue or prussian blue in place of ultramarine, is an especially strong near neutral triad.)

An alternative approach is to identify identify one of the triad as the key color, such as carmine in the scheme on the right (above), and mix a range of unsaturated analogous hues from it in combination with the other two triad colors. The overall balance in the color harmony, and the radically different directions this harmony can be taken by the relative positioning and emphasis of the three dominant hues, make the triadic scheme extremely flexible and fun to explore.

The triadic colors do not have to be equally spaced around the hue circle. In the scheme at right (top), the magenta can be replaced by a middle red: this shifts the center of balance toward yellow, increases the saturation of orange mixtures, and shifts the triadic scheme toward a split complementary palette.



triadic color harmonies

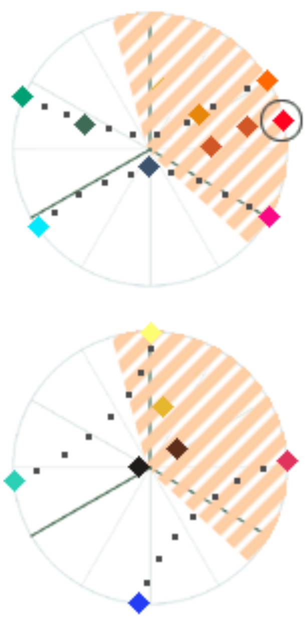
the key color is circled

Tetradic. The last color harmony, the **tetradic**, is based on four colors, two pairs in complementary relation to each other and the remaining two pairs in analogous relation. The two complementary pairs form the two diagonals of a rectangle or square on the hue circle, with the analogous colors as the two short sides.

To create a tetradic palette, (1) choose a key color at the edge of the hue circle, (2) choose a complementary color opposite it on the hue circle, (3) choose a "warm" or "cool" hue within the analogous color range of the key color, and (4) choose a "warm" or "cool" hue within the analogous color range of the complementary color. You can use any mixture of these colors with themselves and with white, black or a dark neutral.

If the color selection forms a square, then the four colors may consist one "primary" hue, its complementary (secondary) hue, and two tertiary hues. Another square color selection, the artists' primaries (http://www.handprint.com/HP/WCL/palette4d.html) palette derived from the Hering unique hues of red, yellow, green and blue, is also a tetradic palette. If a rectangle, the four dominant hues will often include two "primary" colors (one warm, the other cool) on the same side of the hue circle, with their two complementary (secondary) colors on the opposite side. The rectangular scheme can also be positioned to consist of four tertiary colors. Either scheme makes it especially easy to mix a wide range of near neutral colors

The usual point of the tetradic harmony is to pit two complementary color pairs against each other, creating tension through the separate complementary contrasts and through the relative dominance of the two pairs. This is especially effective when one complementary axis represents the color of light, and the other the color of surfaces (landscape).



tetradic color harmonies

the key color is circled

The two short sides of the rectangle can form analogous colors around a single complementary contrast for example, warm hues against cool hues then the tetradic scheme is an expanded form of the split complementary color harmony (as described above). However, a tetradic palette includes so much of the hue circle, that free mixtures among the four anchor colors can eliminate a sense of harmony altogether. The color design should strive to preserve a dominant key color or "center of gravity" in the mixtures. The major tension is usually between a warm or cool color.

eight approaches to color harmony

Now let us explore the idea of **color harmony** by looking at eight different implementations of the concept (links, right). These illustrate color harmony defined in terms of: (1) the physical attributes (wavelengths) of spectral light; (2) the subjective basis of complementary colored shadows; (3) the abstract qualities of color mixture ("primary" colors); (4) the visual or empirical effects of color combinations; (5) the geometrical color relationships within a pigment mixture color solid; and (6) the geometrical relationships within a perceptual color space; (7) colors lying on a plane within a uniform color space; and (8) color relationships within a hybrid color space created explicitly for industrial color design applications.

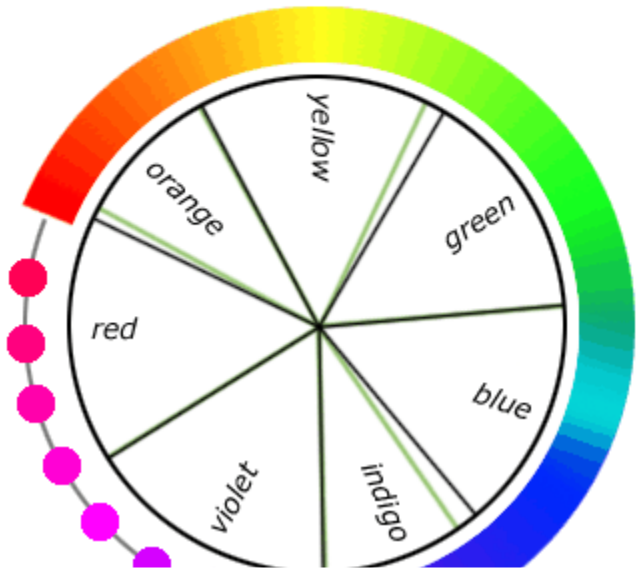
This selection is not exhaustive or even representative of historical systems of color harmony. I've chosen these systems to illustrate the common assumptions used to systematize the behavior of color mixtures and schemes of color harmony.

1. Newton's Hue Intervals. The hypothesis that harmony in color was determined by proportions or ratios, like harmony in music, was advanced by Isaac Newton in

a letter to the Royal Society in 1675. His system of color harmony echoes the writings of the Greek philosophers Aristotle and Theophrastus (who attributed color to the whole number proportions of different basic colors), the integer ratios that were used by Greek Pythagorean philosophers to describe the relationship among musical tones on a vibrating string, and the mathematical mysticism of the medieval "music of the spheres".

Newton's system is based on the *refrangibility* or angle of refraction that is a consistent property of different light wavelengths. This spreads out the colors of light into the characteristic spectral order *red, orange, yellow, green, blue, indigo* and *violet* when light is passed through a glass prism. To describe the relative spacing of spectral colors, Newton inscribed a diatonic musical scale from D to C (more accurately, the Dorian mode), clockwise around the circumference of his hue circle (http://www.handprint.com/HP/WCL/color2.html#huecircle) of 1704:

Describe a Circle ADF, and distinguish its Circumference into seven Parts DE, EF, FG, GA, AB, BC, CD, proportional to the seven Musical Tones or Intervals of the eight Sounds, Sol, la, fa, sol, la, mi, fa, sol, *contained in an eight* [octave], *that is, proportional to the Number 1/9, 1/16, 1/10, 1/9, 1/9* [corrected], *1/16, 1/9. Let the first Part DE represent a red Colour*. (*Opticks,* Book I, Proposition VI, Problem ii)



newton's diatonic division of spectral hues (1704)

Newton's division of the hue circle in a diagram (black lines), and in fractional diatonic sections (green lines); the spectral hues in wavenumber spacing are aligned to match the modern perceptual scaling in which extraspectral mixtures (dots) span one fourth of the total circumference

Correcting an apparent typo and rescaling the sum of the fractions to equal 1, these ratios apportion the hues into sections that are 60° (*red, green, blue, violet*), 54° (*yellow*) or 33° (*orange, indigo*) wide. Fitting the spectrum so that "yellow" and "blue" (cyan) fall in the center of their sections, Newton's divisions correspond reasonably well to the prismatic spectrum (which distributes light evenly by wavenumber). However these divisions are not definitive, because a different spectrum spacing is produced in the spectrum from a diffraction grating (which distributes light evenly by wavelength (http://www.handprint.com/HP/WCL/color1.html#spectrum)). However we can see, in the broad span of hues assigned to "yellow" or the large span of "red" and "violet" hues that must be extraspectral mixtures, that Newton's scheme is visually subjective and apparently forced by his musical analogy.

Nor was this Newton's only stab at the problem. Just as a vibrating string or resonant pipe produces an octave tone (that is, double the sound frequency of the fundamental tone) when stopped at its half length, Newton proposed that the visible spectrum represents only one half of a fundamental resonance that we cannot see. He then identified hue boundaries as harmonic fractions of the visible "second octave" (diagram, below), just as the Pythagoreans had done with vibrating strings.

newton's harmonic division of spectral hues

the vertical lines define the boundaries between the basic hues (right to left) red, orange, yellow, green, blue, indigo, violet; circular hue divisions centered on *yellow* shown along top edge

Unfortunately, when these intervals are coiled into a circumference, they do not correspond at all to the fractional spectrum partitions illustrated on the hue circle: *red* occupies a 45° segment, *green* and *blue* each 60° segments, and *violet* an 80° segment. Thus, Newton applied the analogy of musical intervals in two different ways!

The metaphor of color as music was intriguing to color savants in the 18th century, particularly in France. Colors were believed to combine to form "color chords" or color harmonies, just as notes can be combined to form a musical chord. The Jesuit French pedagogue Louis Bertrand Castel (http://www.handprint.com/HP/WCL/color6.html#holdouts) built and performed on a "chromachord," a harpsichord that simultaneously sounded musical notes and flashed colored cards corresponding to each tone. Related strategies reappear in the 20th century as the *"clavier à lumières"* designed to accompany orchestral works by the Russian composer Alexandr Scriabin or the "color organ" of Hungarian composer Alexander Laszlo.

There are three difficulties with the idea of color "notes" (defined as the dominant wavelength (http://www.handprint.com/HP/WCL/color3.html#colormakinghue) or "pure hue") as the basis of color "harmonies". Perhaps the most obvious is that musical vibrations span a potentially very large range of frequencies, from 20 hertz up to 20,000 hertz, or roughly 10 octaves. Visible light frequencies, between 400 terahertz and 750 terahertz, don't even span one "octave".

Musical harmonies are always fixed ratios related to a fundamental frequency. If the fundamental tone has a frequency of **x**, then the interval of the major third is at the frequency of **5/4x**, the fourth at **4/3x**, the fifth at **3/2x**, and the octave at **2/1x** (double) the fundamental frequency. In contrast, there is no consistent wavelength or spectral spacing relationship in colors of a particular hue (*yellow* is created by pure "yellow" light, and also by the mixture of "red" and "green" light), and there is no perceptual consistency in the systematic pattern of musical "chords" to spectral mixtures. In Newton's scheme, for example, a color chord at the interval of the third includes *violet-blue, blue-yellow, green-orange* and *yellow-red*, which are visually very different (e.g., *blue-yellow* and *green-orange* are strongly contrasted near complementary colors, while *violet-blue* and *yellow-red* are similar or analogous colors).

Third, sound is largely independent of context, but color is not. The ear provides a unique sound receptor or group of receptors for each sound frequency, so the base frequency and all harmonics of any sound can be perceived as a separate sound profile regardless of other sounds mixed with them: we can carry on a conversation while music is playing. In contrast, color is affected by context (http://www.handprint.com/HP/WCL/color4a.html) in a way that musical tones are not: the same colors have a very different impact if "played" at low or high illumination, or when surrounded by other colors.

The many other schemes of "color as music" have looked for ways around these objections; Scriabin appears to have used the circle of fifths and assigned single musical tones to single colors in a synesthesic mapping of music to color to mood. For our purposes, Newton's musical metaphors illustrate four features of "color harmony" that reappear in many later color systems:

there is the arbitrary application of a geometrical or mathematical order to color relationships

the mathematical or geometrical system often does not predict, explain or conform to important visual color facts (e.g., the spacing of spectral hues, the visual significance of color intervals or "chords", etc.)

the "colors" manipulated by the system are really concept colors (hues, independent of lightness or saturation); perceptually important color variations (in brightness, lightness or saturation) are excluded from consideration

These features are not unique to "musical" color systems: as we see next, they reappear in color systems that have nothing to do with musical metaphors.

2. Rumford's Complementary Colors. Benjamin Thompson (http://en.wikipedia.org/wiki/Benjamin_Thompson), Count Rumford (1753-1814) was one of those scintillating 18th century naturalists and inventors whose explorations of the physical world bridged theoretical and practical concerns. He studied the nature of thermodynamics and heat, and applied his insights to the better design of worker housing, stoves and coffee pots; he found ways to measure illuminance in order to determine the optimal lighting in workhouses for the poor. During these photometric studies he noticed and reported the complementary shadow hues (http://www.handprint.com /HP/WCL/color18b.html#shadowcolor) produced by two lights, one white and one colored, casting shadows from the same object.

Rumford's account of these observations, summarized as "Conjectures Respecting the Principles of the Harmony of Colours" in 1794 (and available in this online book (http://books.google.com/books?id=VDxJlgUeA-sC)), is worth quoting at length because it recites, with admirable brevity, the 18th century understanding of complementary colors:

"*Whenever a beam of* coloured light *of any species, and a beam of* white *or* colourless light *of equal intensity, arriving in different directions and at equal angles of incidence at a plane white surface, illuminate that surface together, if a solid opaque body of any kind be placed in each of these means of light, just before the illuminated plane, in such a manner that the two shadows cast on the plane by these opaque bodies may be near each other, the intensities of these shadows will be equal, and they will both appear to be coloured, but of very different hues. That which is illuminated by the* coloured light *will be of the colour of that light which is what would naturally be expected to happen by a person who had never seen the experiment, but that which is illuminated by the* colourless light*, and by that alone, instead of appearing colourless, will* appear *to be as deeply coloured as the other, but of a different hue.*

The two colours exhibited by the two shadows appear in all cases to harmonize in the most perfect manner, or, in other words, to afford the most pleasing contrast to the view.

These two colours are always such that, if they could be intimately mixed together, the result of that mixture would be perfect whiteness; *and, as whiteness results from the mixture of all the differet colours in certain proportions, the two shadows may be considered as containing all the colours in their just proportions, and the colour of the one shadow may with propriety be said to be the* complement *of the other.*

Two neighbouring colurs are then, and only then, in perfect harmony when the intimate mixture of both would produce perfect whiteness; and hence it appears that, when two colours harmonize, one of them at least must necessarily be a compound color.

In the experiment of the coloured shadows, the colour exhibited by one of the shadows only is real, that of the other is imaginary*, being an optical deception, occasioned in some way unknown to us by the colour actually present and by the effects of the different lights and shades. The* imaginary colour [green blue]*, which may be said to be* called up in the mind *by the other* real colour [orange red]*, does not, however, appear to be at all inferior to the real colour either in lustre or in the distinctness of its hue.*

... To every colour without exception, whatever may be its hue or shade, or however it may be compounded, there is another in perfect harmony to it, which is its complement, and may be said to be its companion."

Rumford confirmed that the white illuminated shadow color was "illusory" by observing that the color disappeared when viewed through a narrow tube that excluded the surrounding surfaces from view. He then described experiments with colored papers (similar to those Michel-Eugène Chevreul would do three decades later), reporting that an illusory green color appeared in a gray strip of paper, paired with a matching strip colored red that was laid beside it on a pink circle within a much larger background of black. He then observed:

But although it may be impossible for painters, with their imperfect colours, *to produce effects that will bear a close comparison with those magic appearances of which we have been giving an account, yet there can be no doubt but that the knowledge of those facts, and of the theory by which they are explained, may be very useful to them.*
The impossibility of producing perfect whiteness by any mixture of painters' colours is a proof of the want of purity of those colours, and of the difficulty of imitating by means of them any of those very striking effects which are exhibited in experiments with the pure prismatic colours."

These observations are consistent with other themes common during the late 18th century, but carry them farther. Newton in 1703 had established that hues opposite on his hue circle would approximately mix to white (http://www.handprint.com/HP/WCL/color2.html#mixingcircle), without claiming any esthetic excellence in this opponency; Moses Harris in 1766 recommended the use of "contrary hues (http://www.handprint.com/HP/WCL/color6.html#harris)" on the hue circle to produce the most effective color contrasts, without calling them specifically *harmonious*.

However, Rumford asserts that the "pleasing" and "beautiful" effect of the illusions demonstrates their esthetic harmony; that the color combinations are "called up in the mind" and therefore an artifact of perception; that the fact they are harder to produce in material colors proves the "impure" nature of pigment mixtures and the "pure" nature of light mixtures; and that complementary hues can be considered "companions" across a variety of color display situations, not just in colored shadows.

One might ask why the *beautiful harmony* of colors observed in shadows should be generalized to any and all colors, if the shadow colors are *illusory*. After all, a variety of paradoxical visual illusions are enjoyable precisely because they reveal a covert trait of human vision, but no one promotes them as esthetic benchmarks. In fact, most 18th century descriptions of colored shadows emphasize that they are striking precisely because they are inexplicable. The appropriate answer is that the shadow harmony depends on color attributes *other than* hue opponency; shadow colors are balanced in lightness and chroma, making them *nuance colors,* and are harmonious across all hue combinations.

Rumford's assumption seems to be that an illusory process creates the color contrast, which detached and sober judgment can recognize as harmonious, separating illusion from discernment. The fact that complementary colors mix to white is not demonstration of *visual* harmony per se, but rather of an inferred "balance" between the two hues. Balance serves as the intellectual justification. The 18th century believed that balance was a component of beauty, which in turn was a sign of the divinely designed orderliness of "Nature's laws". Harmony and balance characterize many aspects of the 18th century's intellectual outlook, but they are very far from universal or even historical European values.

Rumford's ideas demonstrate the distorting effect of factual ignorance within a morally defined world view. The 18th century understood that paints mixed differently from lights, but could not explain why; instead the moral terms "pure" and "impure" were recruited as explanation, and light mixtures were chosen to identify the most "perfect" color mixtures. Although these terms literally indicate the lack of an impartial scientific vocabulary, they also illustrate the routine acceptance of moral terminology in 18th century discourse. Ideas, experiences and phenomena were commonly ranked as higher or lower on a scale of value, and the reader's connoisseurship of such rankings was assumed to guide his educated taste.

All these traits predisposed 18th century "color theory" to reify color sensations as *concept colors,* which allowed "pure" color ideas to define the choice of material colors in any real world application. As Rumford charmingly says, *"By experiments of this kind, which might easily be made, ladies may choose ribbons to their gowns; or those who furnish rooms may arrange their colours upon principles of the most perfect harmony and of the purest taste."*

What is surprising is that many 21st century artists still espouse the complementary color dogma, and follow Rumford's decision to generalize *concept color* relationships across all color applications.

3. Arnheim's Concords and Discords. Newton's approach to color through the physical properties of light languished until the late 19th century, when it was taken up by German perceptual psychologists (http://www.handprint.com/HP/WCL/color6.html#helmholtz). Instead, the artistic "color theory" tradition, from the early 18th through the 20th centuries, emphasized the color mixing behavior of paints, and the analysis of color in terms of three subtractive "primary" colors.

At first, the artists' tradition preferred the geometric metaphor of a "color wheel" (http://www.handprint.com/HP/WCL/color6.html#materialtrichromacy), which was created by adapting the hue circle that Newton proposed for the analysis of light mixtures (http://www.handprint.com/HP/WCL

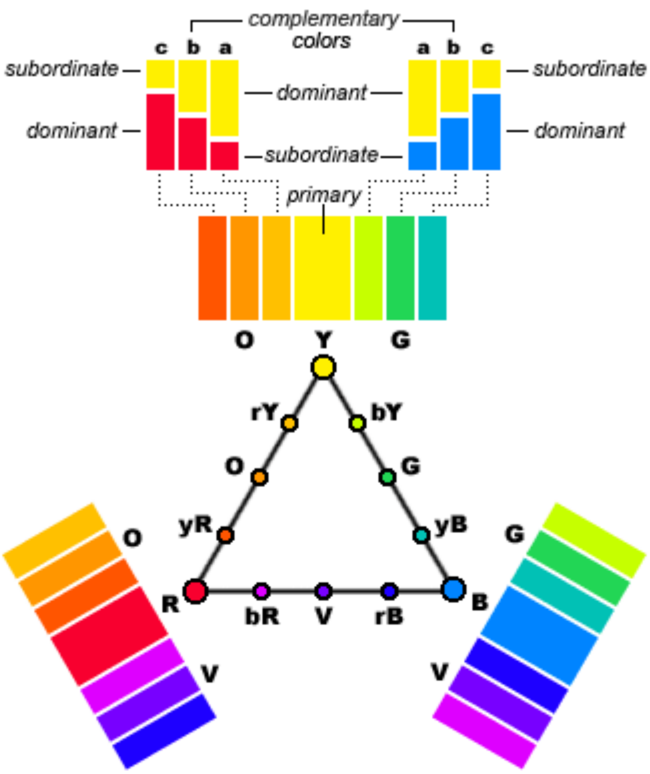
/color2.html#mixingcircle) to the analysis of subtractive color mixtures, with hues spaced around the circumference so that the three subtractive primaries were equally far apart. This system appears in the color wheels published by Moses Harris (http://www.handprint.com/HP/WCL/color6.html#harris) in 1766. Then, late in the 19th century, the artists' tradition shifted to the use of a trichromatic mixing triangle (http://www.handprint.com/HP/WCL /color6.html#maxtriangle), as exemplified in color research by James Clerk Maxwell (http://www.handprint.com/HP/WCL/color6.html#maxwell) and German psychophysicists. A triangle was also the logical format for early pigment mixture color models developed by Tobias Mayer (http://www.handprint.com /HP/WCL/color6.html#mayer) and Johann Lambert (http://www.handprint.com/HP/WCL/color6.html#lambert).

In his book published in 1879, Ogden Rood (http://www.handprint.com /HP/WCL/book3.html#rood) gave detailed instructions for how to use an additive (visual) mixing triangle (http://www.handprint.com/HP/WCL /color6.html#rood) to represent the hue and saturation of artists' pigments that had been analyzed with a color top (http://www.handprint.com/HP/WCL /colortop.html); but by the early 20th century John Sloan was recommending the use of a subtractive mixing triangle (http://www.handprint.com/HP/WCL /color6.html#sloan) that excluded the accurate representation of color saturation (all pigment colors where contained inside the triangle), and grossly distorted the unequal hue separation (http://www.handprint.com/HP/WCL /color13.html#truespace) between "primary" colors in order to make a geometrically tidy representation. It is within this tradition of tidy geometries that the academic art theorist Rudolf Arnheim (http://www.handprint.com/HP/WCL /book4.html#arnheim) (1904-2007) published a theory of color harmony in his *Art and Visual Perception* (1954).

The fundamental building blocks of Arnheim's color theory are the traditional three subtractive "primary" colors (http://www.handprint.com/HP/WCL

/color18a.html#subtractiveprimaries) (still defined, in Arnheim's time, as **R** red, **Y** yellow and **B** blue), which he terms *fundamentals*. He deduces their "fundamental" status from the fact that they cannot be mixed from other colors and are more saturated than any mixture they create.

Arnheim next considers the **mixture proportions between two fundamentals** (assuming that all three fundamentals have the same tinting strength (http://www.handprint.com/HP/WCL/intstud.html#step15)). He presents these as three **chromatic continua** which represent the mixtures of each fundamental with the other two fundamentals (diagram, below).



rudolf arnheim's primary mixtures

the color triangle, with the chromatic continuum centered on each primary

For simplification, Arnheim restricts each continuum to just three mixtures. The mixture of two fundamentals in equal proportions produces a *complementary color*. However, Arnheim treats the complementary colors as perceptually unique in the same way the fundamentals are, which limits the considerations of color harmony to the six remaining unequal mixtures, the *tertiary colors*. These are mixtures in which the mixture proportion of one primary paint is *dominant* and the mixture proportion of the other primary is *subordinate*.

The tertiary colors then can be combined as *color pairs* in only four basic patterns:

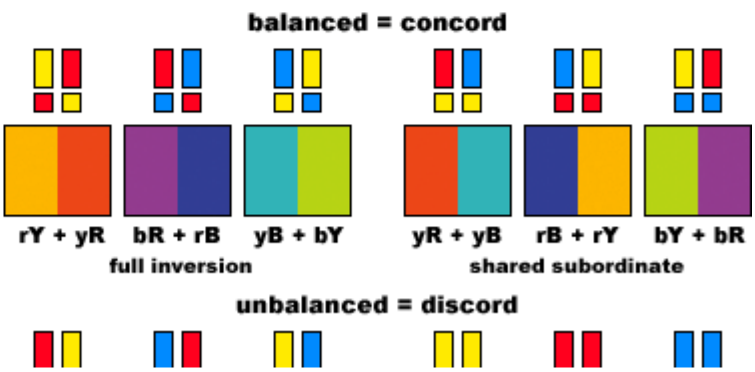
full inversion (creates a color bond or concord) - only two fundamentals are used, with each fundamental in the dominant position in one color (these are *analogous colors*)

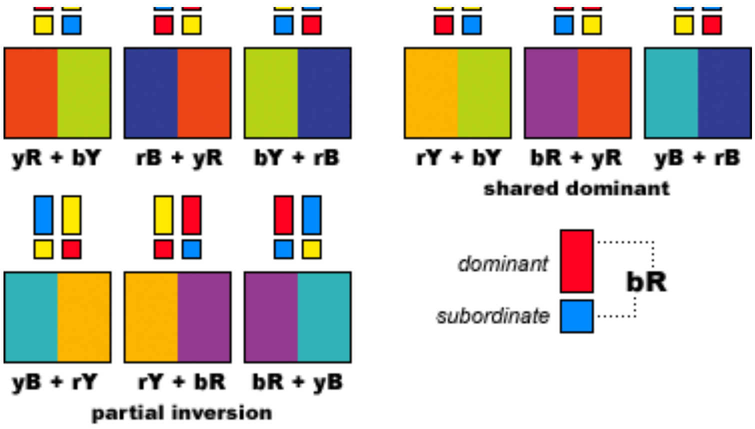
partial inversion (creates a color contrast or discord) - in a full inversion pair, the subordinate fundamental of one color is replaced by the missing third fundamental

shared dominant (creates a color contrast or discord) - the dominant fundamentals are the same but the subordinate fundamentals are different; and

shared subordinate (creates a color bond or concord) - the subordinate fundamental is the same in both colors, but the dominant fundamentals are different (these are *complementary colors*).

These permutations result in 15 unique pairings of six tertiary colors depending on the "primary" that is dominant or subordinate in each. This produces the inventory of tertiary color contrasts shown in the diagram (below).

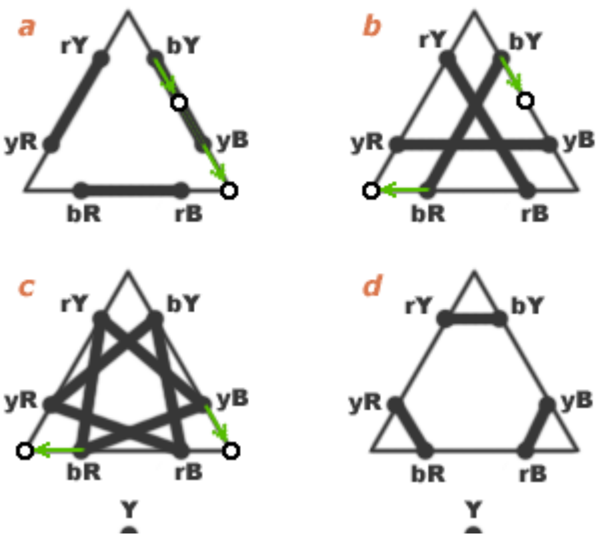


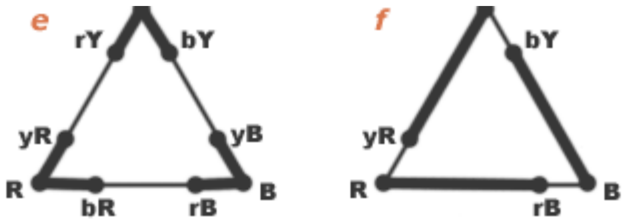


arnheim's 15 tertiary concords and discords

full inversion: only two primaries in color contrast, switched between dominant and subordinate positions (these are analogous colors); **shared subordinate**: single primary in subordinate position, remaining two primaries paired in dominant position (these are also *complementary colors*); **shared dominant**: single primary in dominant poisition, remaining two primaries paired in subordinate position; **partial inversion**: one primary fills diagonal dominant/subordinate position, remaining two primaries paired in opposing diagonal position.

The differences among these various tertiary combinations are somewhat easier to see when they are represented on the "primary" color triangle (diagram, below).



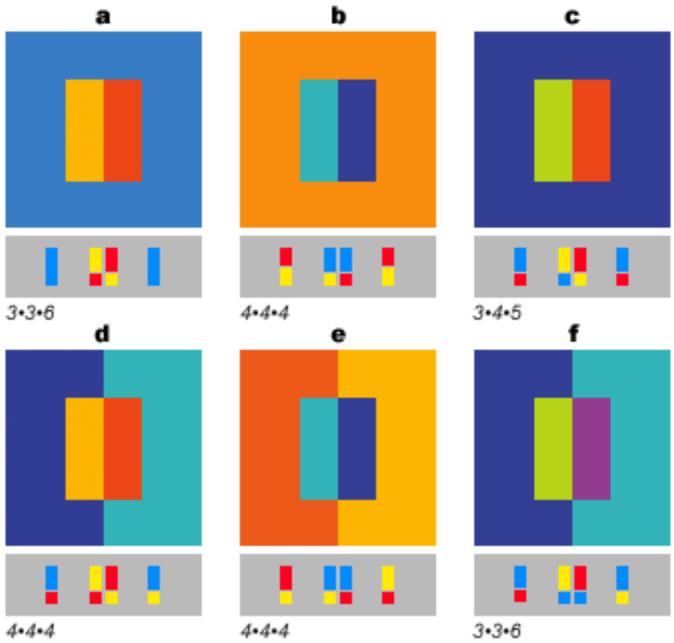


arnheim's six tertiary contrasts (1954)

bold lines connect pairs of color mixtures to be compared as either harmonious or discordant; **a**: full inversion [harmonious, equals primary+adjacent secondary], **b**: shared subordinate [harmonious, equals primary+complementary], **c**: partial inversion [discordant, equals two primaries or two secondaries], **d**: shared dominant [discordant]; shown also are **e**: fundamental dominant [discordant], and **f**: fundamental subordinate [harmonious]

This diagram allows us to shift Arnheim's tertiary harmonies around the hue triangle (green arrows) so that one of the colors occupies the "primary" location, which makes them recognizable in terms of the standard around a hue circle. We discover that the harmonious full inversion pair (**a**) corresponds to a primary color with one of the secondary colors adjacent to it (e.g., **bY+yB** is the same as the primary **B** with the secondary color **Y+B**); the harmonious shared subordinate pair (**b**) corresponds to a primary with its complementary color; and the discordant partial inversion pair (**c**) corresponds to two primary or two secondary colors. (The fact that some of Arnheim's tertiary mixtures are visually equivalent to hue harmonies that he excludes from analysis is an unexplained pecularity of his emphasis on the fundamental colors.)

Arnheim's original presentation was theoretical and diagrammatic only, but his predictions about color harmony and discord were subsequently elaborated and illustrated as printed color matching examples by Augusto Garau (in his *Le Harmonie del Colore,* 1984). The diagram (below) shows the six principal color contrasts that Garau discusses.

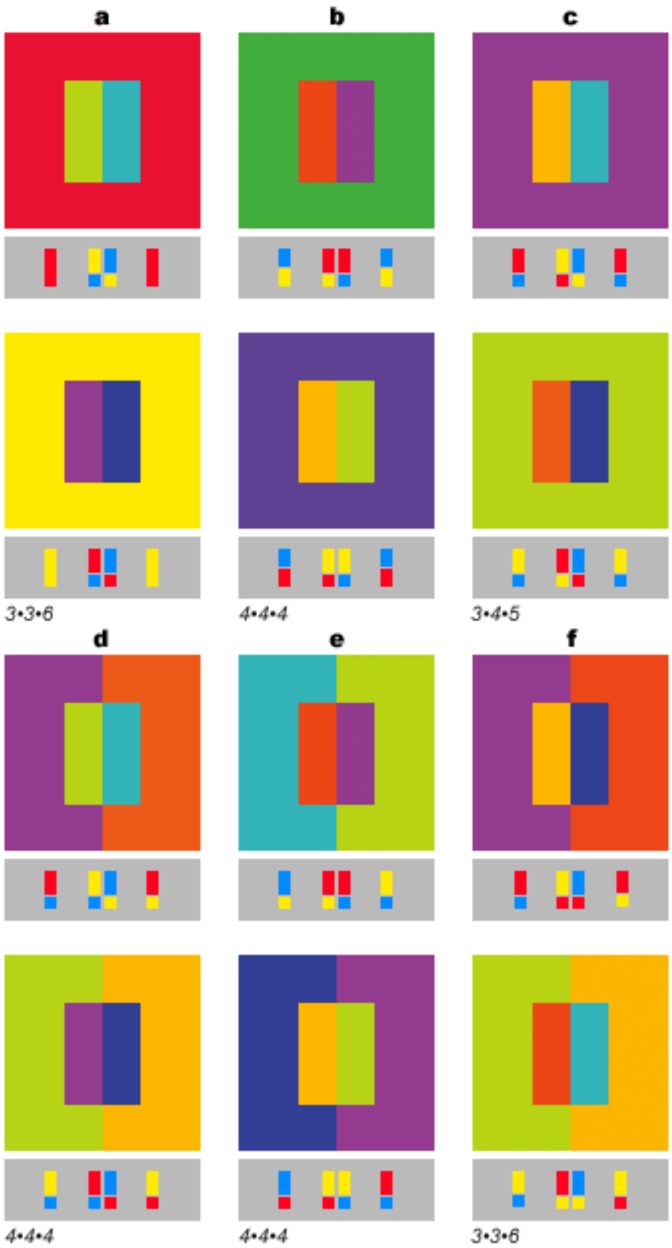


Garau's tertiary contrast illustrations

with the blue **B** "primary" in all pure color or dominant variations: (**a**) full inversion pair on background of third primary; (**b**) shared dominant pair on background of complementary color of dominant primary; (**c**) partial inversion pair on background of two least dominant primaries in full inversion; (**d**) full inversion pair on background of complementary colors; (**e**) shared dominant pair on background of complementary colors; (**f**) shared subordinate pair on background of subordinate primary in shared dominant pair. (Small numbers indicate total quantity of each primary across all colors in the figure; an electronic CYMK palette was used to mimic the printed color theory illustrations.)

By the way these color contrasts are presented, it is clear that the for both Arnheim and Garau is the appearance of colors as large color areas rather than in pattern, representational or environmental contexts: in effect, "color harmony" means that each color brings out the true color character of all colors around it.

The mixtures above all contain the blue **B** primary either in pure form or in the dominant position. In the interest of fair evaluation, here are the same examples with the mixtures defined by the red **R** or yellow **Y** primary in the pure and dominant variations.



Garau's illustrations with the other two "primaries"

examples of each type of contrast with the red **R** "primary" (upper row) or yellow **Y** primary (lower row) in the shared dominant positions; see caption to previous figure for explanation of contrast patterns. (Small numbers indicate total quantity of each primary across all colors in the figure; an electronic CYMK palette was used to mimic the printed color theory illustrations.)

Arnheim predicts that all examples under the same letter label (**a**, **b**, **c**, etc.) will appear similarly harmonious or discordant no matter which primary color is dominant. This seems to me obviously not true. Two examples: the figure **a** with a pure blue background appears much more attractive than the figure **a** with a pure yellow background; and the figure **d** above, composed of analogous orange and gold over analogous blue and blue green, appears much more harmonious than the same figure below, composed of dissimilar yellow green, green blue, orange and purple.

Inconsistencies in Arnheim's color predictions arise partly because his analysis emphasizes proportions of primary *hues* without considering the effect of saturation and value on color harmony. And, as with all abstract color systems, Arnheim confuses hue relationships that need to be kept distinct. Thus, he assumes that green or orange, as secondary colors (equal primary mixtures), will have equivalent contrast effects in color design for example, that the complementary contrast between green and red has the same impact as the contrast between orange and blue (or yellow and purple). This is again obviously not true.

But the real difficulty is that Arnheim uses proportional relationships among abstract "fundamentals" to specify the proportional mixing recipes of paints, which in turn are used to determine the relative *esthetic impact* of the mixtures conflating concept colors, material colors and visual colors in a single geometrical scheme.

How could we put Arnheim's system to a test? If we permit all pairwise combinations of the 12 hues on a tertiary color circle (so that we include combinations that display the pure "primary" and equal mixture secondary hues, and exclude any mixture with white or black), then there are 66 possible color pairs, 660 posible combinations of a color pair on a solid background of a third color, and 2970 possible combinations of two colors on a split background of two different colors. We would have to ask a group of artists to view each color combination in isolation, and judge it as relatively "harmonious" or "discordant", then look for consistent patterns in their judgments. To my knowledge, this has never been done.

Instead, Arnheim's color system rests entirely on the *a priori* assertion of geometrical regularity on a dogmatic foundation of "fundamental" colors, not on an empirical study of *how color behaves*.

4. Chevreul's Empirical Color Harmonies. I've said that the scientific, quantitative study of color mostly languished from Newton's age until the mid 19th century, and that artistic "color theory" in the interim focused primarily on concept "primary" colors or pigment mixture models (http://www.handprint.com/HP/WCL/color6.html#mayer) displayed in a triangular or circular framework. Fortunately, there were several 18th and 19th century researchers who explored the qualitative behavior of color under a variety of viewing conditions. This tradition includes Georges-Louis Leclerc (Comte de Buffon), Benjamin Thompson (Count Rumford), Jan Purkinje (http://www.handprint.com/HP/WCL/color2.html#heringtheory), Erasmus Darwin and J.W. von Goethe (http://www.handprint.com/HP/WCL/goethe.html), among many others. This tradition directly informs the empirical color studies of Michel-Eugène Chevreul.

Chevreul is most widely known for his *law of simultaneous color contrast,* first enunciated in his encyclopedic study (http://www.handprint.com/HP/WCL/book3.html#chevreul) of color effects:

"In the case where the eye sees at the same time two contiguous colors, they will appear as dissimilar as possible, both in their optical composition [hue] *and in the height of their tone* [mixture with white or black]. *We have then, at the same time,*

simultaneous contrast of colour properly so called, and contrast of tone." (*The Principles of Harmony and Contrast of Colors,* 1839)

But Chevreul's real claim to fame may be his hands on, empirical and exhaustive study of color harmony an enormous labor of visual color experiments that he inflicted democratically on himself, his colleagues and his visiting clients at the Gobelins textile factory where he was chief chemist. His book is filled with hundreds of specific color observations such as these:

"[Combinations of Non-Complementary Colors with Gray]

Yellow and Green
(231.) 1. Yellow and Green, etc. [repeated as a series]
2. Gray, Yellow, Green, Gray, etc.
3. Gray, Yellow, Gray, Green, Gray, etc.
Gray allies well with Yellow and Green; but the combinations (2) and (3) are a little dull, and inferior to those in which Black replaces Gray."

. . .

"[Colors In Paper Hangings With Designs In a Single Color]

(452.) Gray patterns upon papers tinted of a light color exhibit the phenomenon of maximum contrast; that is to say, they gray appears colored with the complementary color of the paper. Thus, conforming to the law:
Gray *patterns on a* Rose *paper appear* - Green
Gray *patterns on a* Orange *paper appear* - Blue
Gray *patterns on a* Yellow *paper appear* - Violet *or* Lilac
Gray *patterns on a* Green *paper appear* - Pink
Gray *patterns on a* Blue *paper appear* - Orange-Gray
Gray *patterns on a* Violet *paper appear* - Yellow"

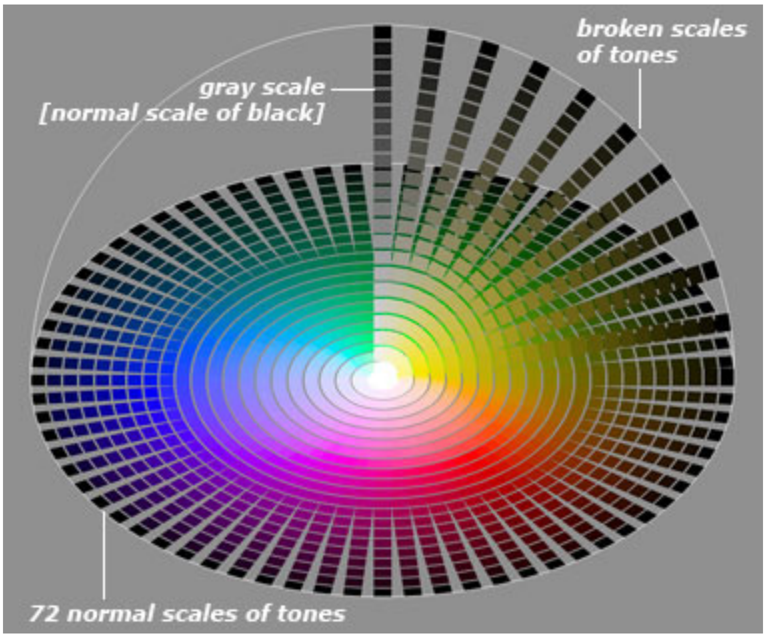
. . .

"[Flower Patterns of Various Colors Printed On a Solid Background]

Yellow Background
(494.) Orange flowers contiguous to the background evidently lose some of their vivacity, in comparison with the appearance on a white background. The whites are less beautiful than upon a red background. The greens are bluer than upon a White background. The roses become bluer, the violets acquire some brilliancy. The whole effect is good, because there is but little yellow in the border, and but little Orange contiguous to the background."

The subtleties of observation gray with yellow and green is "a little dull"; "orange gray" (rather than just "orange") appears in the paper hangings on blue suggest the attention to the facts of perception that is the hallmark of an *empirical* color study. This focus on *color observations* means that concept colors and geometrical forms are no longer the authority for artistic color advice.

Because the observed simultaneous contrasts in color appearance produced changes in hue, lightness and saturation, Chevreul carefully described the procedures to create a hemispherical color model (http://www.handprint.com /HP/WCL/chevreul.html#hemisphere). The fundamental unit in this model was the *normal scale of tones* a color scale in 22 equal lightness (value) steps, exemplified by mixing a pure color with white (at step 0) or black (at step 22) but not both. Each normal scale step would be adjusted to have the same lightness (value) across all hues, which provided a consistent framework for his use of the terms *scale* and *height of tone*. To create the hue circle, he specified 72 separate normal scales of tones, arranged radially with the black or 22nd step at the circumference. Standing vertically at the white center of the hue circle was the *normal scale of black,* a 22 step gray scale; this was mixed in 9 incremental proportions with a normal tone scale to create 9 *broken scales of tones* for each hue (image, below).



chevreul's color model

the hue circle is exemplified by 72 normal scales of tones, arranged with white at the center and black at the circumference; as shown for yellow, each normal scale produced 9 broken scales of tones by means of increasing proportional mixtures with the achromatic gray scale located as the vertical axis of a hemisphere

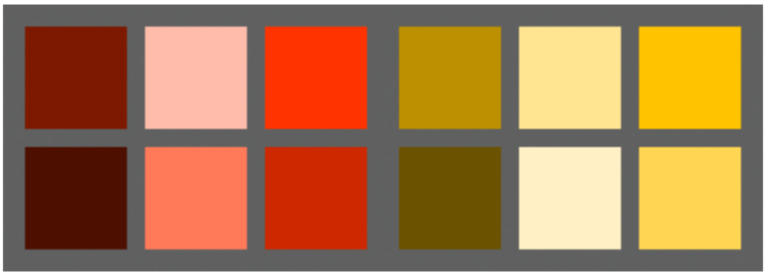
In addition, Chevreul carefully considered the problems that must be solved to make a physical color model, listing the visual proportions necessary to produce the broken scale mixtures, and advising that if no suitably intense pigment or pigment mixture was available to exemplify one of the 72 normal scales in his hue circle, then that hue should just be omitted from the model. Even so, I don't believe a physical model of Chevreul's system was actually created during his lifetime; instead, images of the normal scale of tones, and the hue circle, were included in his book as impressive large format lithographic illustrations.

Summarizing his color observations, Chevreul identified six types of color harmony (http://www.handprint.com/HP/WCL

/book3.html#chevreulharmonies) or harmonious contrast (listed here in my paraphrase):

First Kind: Harmonies of Analogous Colors

harmonies of scale: *a single pure hue mixed with various proportions of black or white (not both).*



chevreul's *harmonies of scale*

for orange red and yellow, in their normal scale of tones

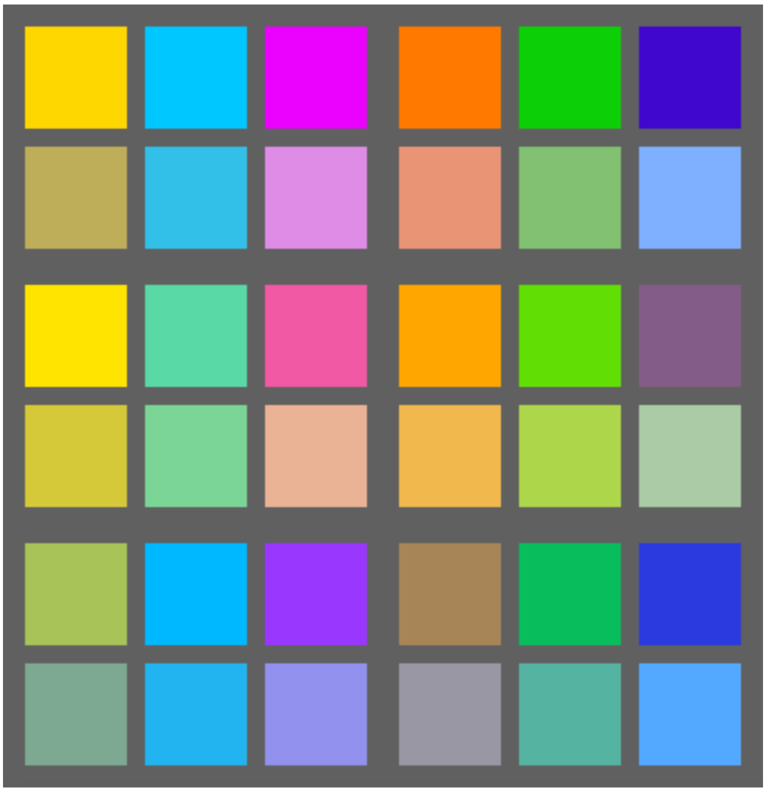
This effect is equivalent to viewing an array of analogous colors under an analogous, intensely colored (monochromatic) light. Colors matching the light and dark colors will appear more saturated, lighter valued colors will appear white or as tints, and colors dissimilar to the light will appear darker valued, many of them approaching black. Chevreul's description implies that these harmonies only lie within a normal scale of tones, but colors selected from the less grayed broken scales of tones would probably be acceptable.

harmonies of hue: *related or analogous hues mixed within a limited range of tone [lightness and saturation].*

chevreul's *harmonies of hue*

This effect is equivalent to viewing a broader selection of related hues under a moderately tinted light: natural examples are desert cliffs at sunset, undersea colors under noon light. There is a wider range of hues, but all are near peak saturation at all levels of lightness.

harmonies of a dominant colored light: *any selection of contrasting colors as they would appear through a "feeble" colored filter or tinted glass*.



chevreul's *harmonies of a dominant colored light*

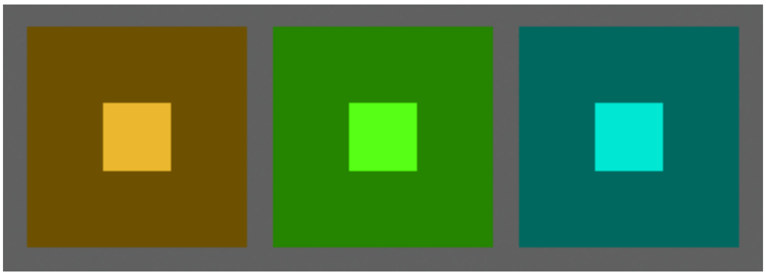
each group of three illustrates the effect on the subtractive and additive primaries, at peak saturation and as nuance colors, of an illuminant or filter varying along a (top) Y/V dimension or a (bottom) R/G dimension

This produces the broadest range of colors of the six harmonies. The filter produces the same color shifts as a moderately colored light source, but the selection of colors permitted is very large. The result does not make all the colors appear analogous, but it grays out and darkens the colors that are complementary to the filter color, and contracts the range of colors toward the filter hue.

What is most striking in this example is the contrasting effect on warm and cool hues. (For a general discussion of the effects of light on visual colors, see this page (http://www.handprint.com/HP/WCL/color18b.html#illuminantcolor).)

<u>Second Kind: Harmonies of Contrasts</u>

harmony of scale contrast: *two colors that contrast strongly in tone [lightness and saturation], both colors taken from the same normal scale of tones.*



chevreul's *harmony of scale contrast*

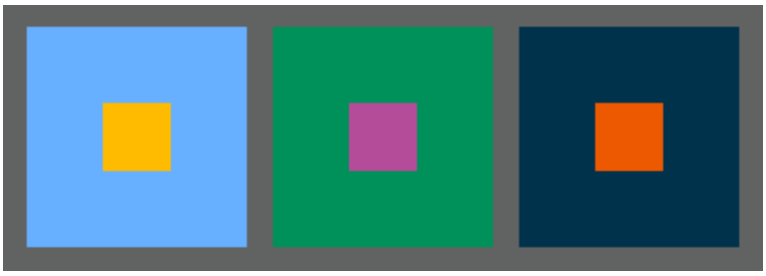
This is just the *harmony of scale* reduced to two contrasting colors; these might be a whitened tone and blackened tone of the pure color, or the pure color in contrast to a strongly darkened tone, etc. The contrast lacks the visual variety of the harmony of scale, and appears constricted or bland.

harmony of hue contrast: *two similar hues contrasted both in hue and in tone [lightness or saturation] between their scales.*

chevreul's *harmony of hue contrast*

This contrast is richer because all three attributes of hue, lightness and saturation can be varied at the same time, though the hues remain similar. Chevreul he describes the hues as "contiguous" or merely "near to each other", and notes that each hue "injures" the other, so that one hue must be made darker (lower in tone) to reduce its effect on the other.

harmony of color contrast: *two colors contrasted strongly both in hue and in tone [lightness and/or chroma]*.



chevreul's *harmony of color contrast*

Chevreul first notes that hues that are not complementary but "very different" should be contrasted in tone, then notes that *"in the harmony of contrast the complementary* [color] *assortment is superior to every other. The tones must be, as nearly as possible, of the same height* [lightness within their normal scales], *in order to produce the finest effect."* He adds that black combines well with light hued or saturated colors (pale blue, yellow, orange, etc.) through harmony of contrast (in lightness and chromatic intensity).

chevreul's arrays for testing color combinations

(top) colors on a medium gray background, used to test combinations with white; (bottom) colors on a light gray background, used to test combinations with black or gray

Using 1 cm colored disks placed 1 cm apart in a row on gray backgrounds (image, above), Chevreul observed the visual impact of pairwise combinations of red, orange, yellow, green, blue and violet, both in isolation and separated by white, gray or black. Thus, he found the combination of white-blue-orange-white to be *"agreeable"*; but in the combination of black-violet-black-red-black he observed that *"red and violet injure each other reciprocally"*. Based on dozens of similar observations, he appended several "propositions" of color combination, offered as his own "peculiar ideas", and listed below in my paraphrase:

In complementary color combinations, white appears most attractively with blue and orange, least attractively with violet and yellow.

The primaries red, yellow and blue combine better with each other than any of them with either secondary color adjacent to it (e.g., red and blue or red and yellow combine better than red and orange or red and violet).

The primaries red, yellow and blue combine better with an adjacent secondary color when the secondary is darker than the primary.

Two colors that do not combine well can always be improved by separating them with white.

Black never produces a bad effect when it is combined with "luminous" (light valued and/or saturated) colors (because of harmony of contrast).

Black produces a good effect when combined with "somber hues" (dark hues such as blue or violet, or blackened hues) or with broken tones of "luminous hues" (red, orange, yellow) by harmony of analogy.

Combined with two colors, black produces a better effect with two luminous colors (including pale tones of blue or violet) than with one somber and one luminous color.

Gray tends to produce dull combinations that are nevertheless not obviously bad.

When combined with somber hues or with broken tones of luminous hues, gray produces harmonies of analogy similar to those of black, but with less "vigor"; gray can also enhance the separation of bad combinations in a manner similar to white.

When combined with a somber hue and a luminous hue, gray may appear with them better than white or black if gray does not emphasize either the lighter or darker color.

When separating two colors that combine badly, the choice to use either white, gray or black depends on the relative lightness of all the colors, and the relative proportion (visual area) of somber to luminous colors.

In two color patterns containing gray, gray is most effective when it is tinted with the complementary hue of the pattern color it is paired with.

Chevreul appended to his basic concepts of color harmony many chapters on their effective implementation in dyes and pigments, and in the color design of everything from flower beds, carpets and interior furnishings to textile patterns, fine art paintings and military uniforms.

The major shortcomings in Chevreul's observations are that he often talks categorically, in terms of concept colors *green* or *blue* are generic terms, without explanation as to *which* green or blue (reddish, yellowish; saturated or dull; light or dark) is intended. Much of his thinking about the causality of color is anchored in the 18th century "primary" color concepts, which have much less relevance to the *visual* impact of color. And, once he had derived his "law" of simultaneous contrast and worked out the rules of contrast for each hue, it is unclear how much this preconception shaped the observations in his color experiments. (I for one find many of the color changes he describes to be quite sensitive to viewing conditions, or entirely unconvincing.)

But Chevreul's effort to stick to the facts of visual observation, and his care to incorporate a very wide variety of color stimuli, color designs and color display situations, makes his work a significant step forward in color science.

Harmonies Based on Color Models. With Chevreul and the work of the German psychophysicists, color science programmatically considers all colors as constituting a color space (http://www.colorcube.com/articles/models/model.htm). The variety and ingenuity of color systems proliferates after 1850, and these all seek to organize the relationships among *all colors,* rather than just hues around the hue circle or tones in their own scale.

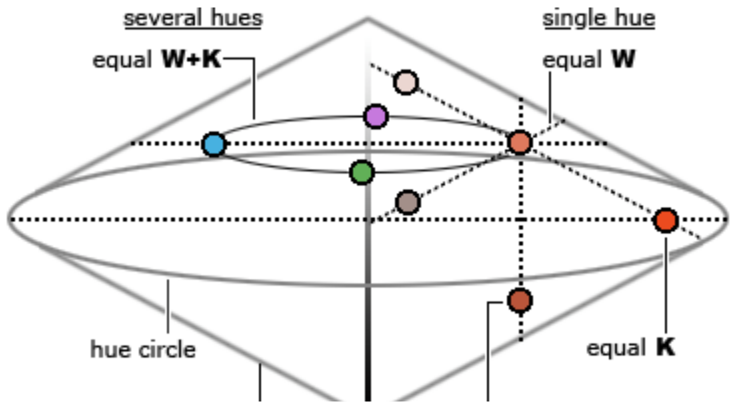
As many color harmony theories for artists are based in various ways on modern color models (http://www.handprint.com/HP/WCL/color7.html), we should briefly recall the major difference between colorant or perceptual (http://www.handprint.com/HP/WCL/color18a.html#colorspace) color system:

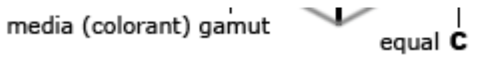
colorant model - created by *equal increment mixtures* in all possible combinations of a set of primary colored pigments, dyes or lights; colors are identified according to the proportions of each primary in the color mixture, and the model defines a *media (colorant) gamut*.

perceptual model - created as dimensions of *equal perceived differences* in all possible combinations of the three colormaking attributes (http://www.handprint.com/HP/WCL/color18a.html#colormakingattributes); colors are identified according to the quantities of each dimension in the color appearance, and the model defines a *perceptual gamut*.

(The color scientist Yoshinobu Nayatani calls these **Type II** (colorant) and **Type I** (perceptual) color order systems.) The key point is that colorant and perceptual models are not equivalent: they define qualitatively different color spaces in which colors are distributed in different ways.

Colorant models define colors as the proportional mixture of (1) a pure primary or mixture of two adjacent primary colorants (to produce a specific hue), (2) a "white" light or white colorant (to produce a specific hue purity), and (3) a proportional luminance or mixture with a black colorant (to produce a specific brightness or lightness). This creates a space in which all colors are labeled by their mixture proportions, and color harmony is often defined as the group of all colors in which one of the three mixture proportions is held constant (diagram, below).



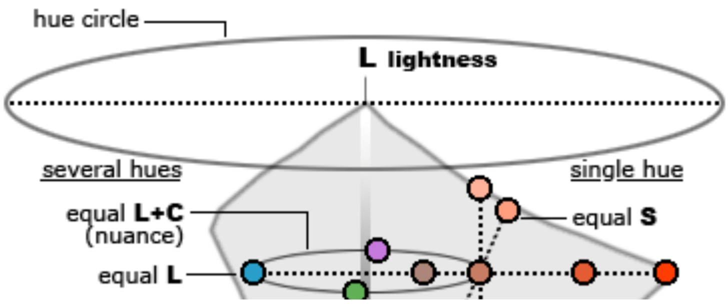


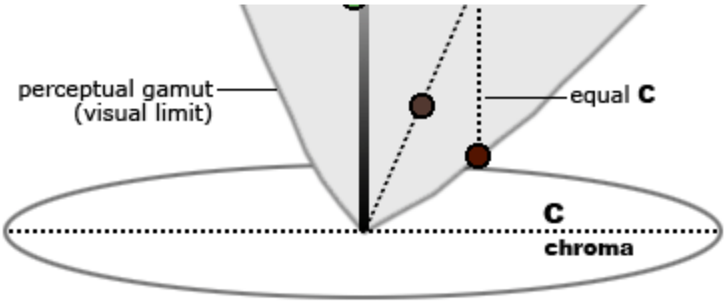
color harmonies defined in a colorant model

C denotes the proportion of one or two mixed "primary" colorants (which locates the color on a mixing hue circle); **W** denotes the proportion of "white" light or a white colorant (to reduce hue purity); **K** denotes the proportion of luminance or a black colorant (to reduce brightness or lightness); all mixtures define a media (colorant) gamut

Thus, "harmonious" colors may be related (within a single hue) as having an equal proportion of **W** (regardless of the relative proportions of **K** and **C**), an equal proportion of **K** (regardless of the proportions of **W** and **C**), or an equal proportion of **C** (regardless of the proportions of **K** and **W**) in the pigment mixture. These are all colors within any column or diagonal row of a hue slice. In addition, colors may be related (across different hue slices) as having equal proportions of **W+K+C** in the mixture, analogous to the perceptual relationship of *nuance*. These procedures define a mixture gamut (http://www.handprint.com/HP/WCL/color18b.html#materialgamut) that contains all the colors it is possible to produce with the primary colorants.

Perceptual color models proceed by first defining three perceptual dimensions some version of the three colormaking attributes, or of the visual opponent dimensions (http://www.handprint.com/HP/WCL/color2.html#opponentdimensions) and then locating any visual color within the space by a process of color measurement.





color harmonies defined in a perceptual model

H denotes the specific hue of the color (in degrees around a visual hue circle); **C** denotes the chroma or hue purity of a color; **L** denotes the lightness or luminance (brightness) of a color; all mixtures define a perceptual (visual) gamut

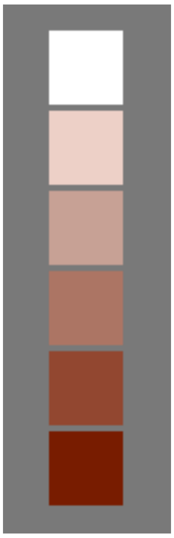
In a perceptual model the dimensions of color harmony are subtly different. Within a single hue, these appearance harmonies include colors of equal chroma (**C**), equal lightness (**L**), or equal saturation (**S**), where saturation is the ratio between the chroma and the lightness (**C/L**) or brightness, defined as a straight line originating at the base of the achromatic scale. Across hues, appearance harmonies include colors of equal lightness, or equal **nuance** all colors of equal lightness *and* equal chroma (or equal saturation).

These color harmony definitions do not represent all those possible. A simple extension is to reverse the definition of saturation to create a set of "whitening" scales, defined as a straight line originating from the white point or pure white color, downward at any angle through any hue slice (diagram, right). These could represent a variety of natural color phenomena, including an evenly oxidizing colored surface, or a surface coated with a clear sealant that turns opaque with moisture, or a surface gradually covered with a fine white dust.

Some 20th century colorant models (specifically Ostwald's *Farbatlas* and the NCS) claim that they accurately represent perceptual color variations, but this is incorrect. Thus, in the NCS, "pure" colors around the hue circle vary widely in lightness (e.g., from yellow to purple), and the incremental mixtures with white are perceptually small for yellow, but very large for purple.

For our purposes, *all* colorant mixture models, even those based on ideal or imaginary primary colors (http://www.handprint.com/HP/WCL/color6.html#CIE1964), or on the RGB outputs (http://www.handprint.com/HP/WCL/color1.html#triprinciples) of the human retina, create unequal or distorted perceptual color differences across different hue slices or lightness levels. These produce significant differences between the color selections identified by the same geometric definition of color harmony in perceptual or colorant color models.

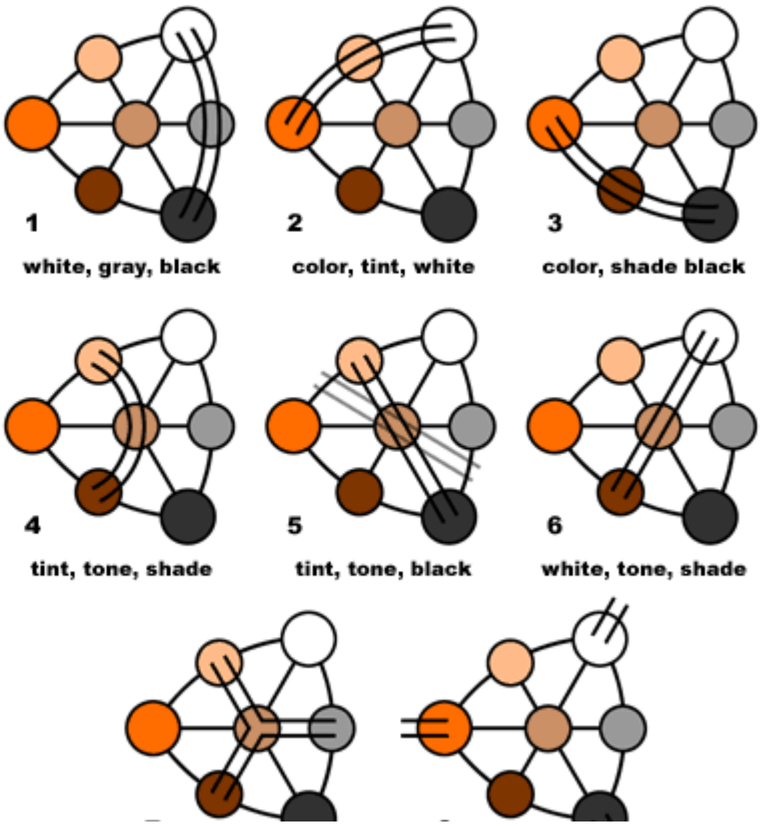
5. Birren's Colorant Harmonies. In his *Principles of Color* (1969), the American color theorist Faber Birren (1900-1988) developed an approach to color harmony based on single hue slices within a colorant mixture color model. In subtractive mixture media these include the Natural Color System (http://www.handprint.com/HP/WCL/color7.html#NCS), Wilhelm Ostwald's Color Harmony Manual (http://www.colorsystem.com/projekte/engl/32oste.htm), and the Pantone printing system (http://www.amazon.com/Pantone-Guide-Communicating-Leatrice-Eisemann/dp/0966638328/).

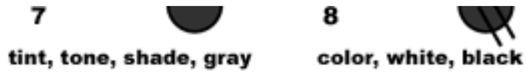


a "whitening" scale in perceptual space

Birren calls his approach a **harmony of color forms** (where "color" is synonymous with "hue"), but it is a straightforward geometical sampling from a generic **monochromatic triangle** that combines all mixtures of a single pure hue ("color", **C**) with white (**W**) and/or black (**K**). This triangle generates four types of compounded or "broken" colors (http://www.handprint.com/HP/WCL/color3.html#stt) as mixtures of white and black (*gray*), color and white (*tint*), color and gray (*tone*), and color and black (*shade*, diagram, right). Birren explains that he got the idea for this color layout from Ewald Hering's (http://www.handprint.com/HP/WCL/color2.html#heringtheory) color geometry, which is of course the foundation for hue pages in the Swedish NCS (http://www.handprint.com/HP/WCL/color7.html#NCSpage) color atlas.

Birren's systematically maps a set of color harmonies onto the triangular schema (diagrams, below). According to Birren, *"the straight line sequences of the color triangle are all natural and concordant. Follow any path and harmony results."*





faber birren's eight color harmonies (1937)

Yes, but what kind of harmony? According to Birren, the different harmony strategies have different visual effects or color design implications:

Scheme **1** (white+gray+black) depends on or emphasizes a *"good architectural order"* heavy black should be opposed to airy white by an intermediate area of gray, as mixing this sequence (as white+black+gray or black+white+gray) may cause the design to appear incoherent.

Scheme **2** (color+tint+white) is *"perhaps the most charming sequence",* used more often in design choices than any other color pattern.

Scheme **3** (color+shade+black) are *"indoor colors ... meant for studio painting ... yet they have great power and force",* the color strategy of old masters such as Rembrandt.

Scheme **4** (tint+tone+shade) is *"the most refined, subtle and eloquent sequence"* on the color triangle, characteristic of Leonardo's *sfumato* style of painting.

Scheme **5** (tint+tone+black/gray) produces the most luminous *"shimmering lights or mother-of-pearl"* effects through the contrasts in color saturation rather than value, depending on whether more or less value contrast is introduced into the scheme (gray lines).

Scheme **6** (shade+tone+white) is in contrast *"unnatural ... unconventional and unfamiliar",* producing a dry or dusty impression mostly found in paintings by El Greco.

Scheme **7** is also refined and restrained (like scheme 4), and establishes the tone color, rather than gray, as the neutral center of a compositon.

Scheme **8** devolves into the harmony of white and black as design carriers, with the pure color as accent or foreground figure.

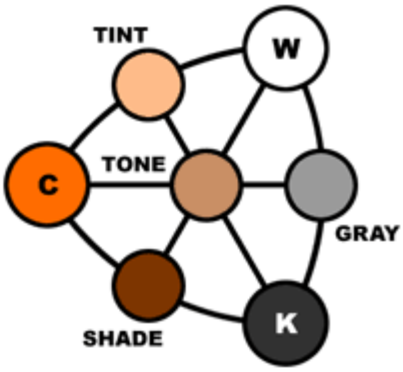
These schemes are extensions of Chevreul's , as Birren admits. They also resemble the color harmonies proposed by Wilhelm Ostwald, which include colors of the same hue that have equal hue content (*isochromes*), equal white content (*isotints*) or equal black content (*isotones*); or colors of different hues that have equal black and white content (*isovalues*). Ostwald asserts that these color series are harmonious because the colors share properties "in certain simple relationships" a theme we have already seen developed, along different lines, by Arnheim.

Birren's color patterns are schematic rather than prescriptive: grays, tints, tones and shades are tokens for loosely identified color categories. A "gray" can be any achromatic mixture between near white and black, and a "tint" can be pure color with some white, or pure white with some color. This invites us to interpret Birren's "geometrical" patterns to include multiple color selections within a series (similar to Chevreul's "harmonies of scale"), or to anchor a series at any arbitrary end color. Thus, series 5 (from black to a tint) and series 6 (from white to a shade), can be defined by almost any tint or any shade, or as mixtures of series 3 and 5 or 1 and 5, or series 2 and 6 or 1 and 6 respectively. The only principle is to minimize color variety when visual clarity is wanted.

The drawback to schematic color ideas is that they lack any reference to the effects produced by different hues. Mixtures with hues that can change color (such as yellow, which darkens to green; or red orange, which darkens to brown; or blue violet, which lightens to blue), the schemas will produce greater visual variety than they will in mixtures with green or blue. Another drawback is that is that the schemes do not account for the context in which the colors will appear.

Scheme **7** may be "refined" when it is used in upscale home decor but it is likely to appear monotonous and stodgy if used for an auto interior or recreational attire. Color mixture has been simplified by introducing ambiguity as to how the color schemas should be applied in real world applications.

If a painter or decorator is struggling with a design choice, Birren's schemas can help to clarify the alternatives, and suggest reasons for using some combinations rather than others. But they can't tell you which are the *optimal choices* for a specific design problem.



faber birren's color triangle

from *Principles of Color (1969)*

6. Munsell's Perceptual Harmonies. The Munsell Color System (http://www.handprint.com/HP/WCL/color7.html#MUNSELL) is arguably the first modern color model based on psychophysical measurements of the perceived differences between physical color samples. It provided the framework for extensive color research into visual color relationships, which branched into two key achievements: the empirical Uniform Color Space (http://www.handprint.com/HP/WCL/color7.html#OSA-UCS) created at mid 20th century by the Optical Society of America, and the algorithmic Color Appearance Model (http://www.handprint.com/HP/WCL /color7.html#CIECAM) created at end of the 20th century by the Commission

Internationale de l'Eclairage (CIE). The agreement between these two color research landmarks is truly impressive (diagram, right). This convergence implies that we now have a reliable enough definition of the perceptual color space to explore perceptual color harmonies with confidence.

Munsell's color model, though historically older, has been revised several times to provide a good scaling of perceptual space in terms of value, hue and chroma. More important, Munsell developed principles of color harmony, applied to the selection of several colors, that were defined as specific paths through his color space. These paths include:

A series on the grey scale

Colors of the same Munsell hue and value, but contrasting chroma

Colors of the same Munsell hue and chroma, but contrasting value

Colors of the same Munsell hue, but contrasted in both chroma and value.

Complementary colors of the same value and chroma (i.e, the same nuance)

Colors in a "diminishing sequence", in which each color is dropped down a step in both value and chroma, as hue is shifted one step in the same direction around the hue circle

Colors on an "elliptical path" in the Munsell color space.

As described by T.M Cleland, Munsell saw balance as a key factor in determining color harmony. Munsell wrote in his *A Grammar of Color* (1921) that:

"The sense of comfort is the outcome of balance. That this approximate balance is desirable may be shown by reference to our behaviour, as to temperatures, quality of

smoothness and roughness, degrees of light and dark, proportion of work and rest."

Once colors were selected in a harmonious combination using these principles, Munsell suggested the artist should balance their relative *color strength* through the visual size of the color display. Munsell defined color strength as the product of Munsell value and chroma. Then the relationship between color strength and color area is defined as:

$$\frac{A_2}{A_1} = \frac{(V_1 * C_1)}{(V_2 * C_2)}$$

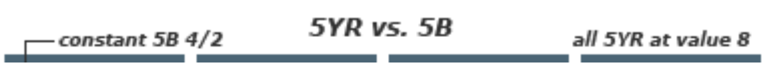
where **A**, **V** and **C** are the area, Munsell value and Munsell chroma of colors 1 and 2. Note that the area ratio is inverted against the color ratio: the color with the weaker color strength is assigned to the larger visual area.

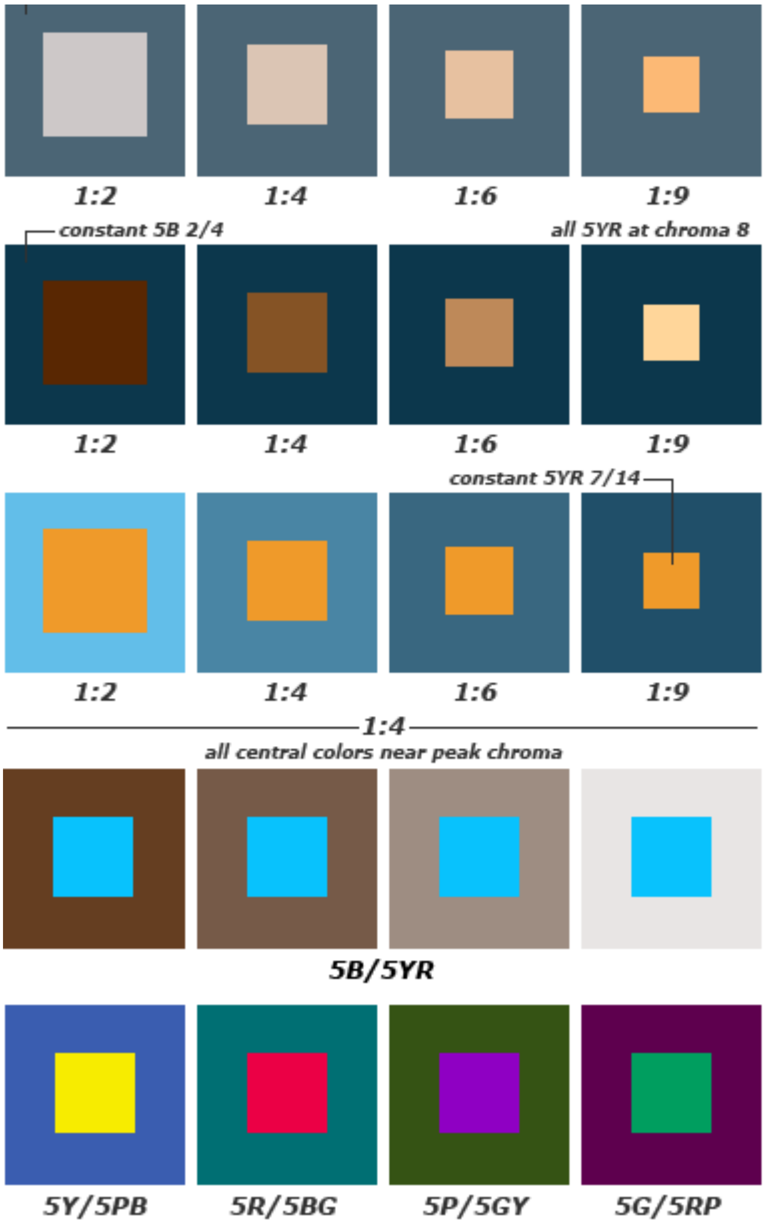
For example, if we have already decided to use a muted dark blue (5B 4/2) with its complementary muted orange yellow (5YR 8/4), then:

$$\frac{\text{5B 4/2}}{\text{5YR 8/4}} = \frac{8}{32} = \frac{\text{4 blue}}{\text{1 orange}}$$

so that the blue area should be visually about 4 times larger than the orange. (Again, note that the color with the smaller product of value*chroma is always assigned to the larger area.)

However, Munsell's formula is in itself ambiguous, as we can just as easily predefine two color areas, then choose any color matchup that produces the correct **V*C** ratio. Thus, a **V*C** product of 8 can be produced by both 5B 4/2 and 5B 2/4, and these two blues can be combined with either 5YR 4/8 or 5YR 8/4. In addition, ratios that are too close to 1:1 tend to produce insufficiently strong contrasts. As the diagram shows (below), these two uncertainties allow for a wide range of color solutions.

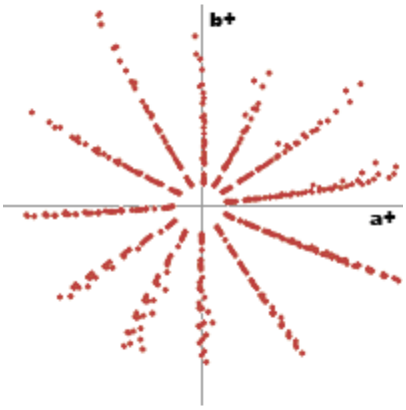




examples of munsell color area harmonies

top row: chroma changes in 5YR at constant value 8 (central squares) produced by reducing area against a constant 5B 4/2 background; **second row**: value changes in 5YR at constant chroma 8 (central squares) produced by reducing area against a constant 5B 2/4 background; **third row**: value and chroma changes in background 5B produced by reducing area of a constant 5YR 7/14 central square; **fourth row**: equivalent value/chroma solutions in a 5B background for the same 5YR 7/14 central square; **bottom row**: harmonious combination of central color near peak chroma and complementary background in 1:4 harmony

To circumvent these problems, Munsell insisted that the color occupying the smaller area should be both lighter valued and more chromatic. As T.M. Cleland explained: *"It will rarely, if ever, be impossible to follow the general principle of printing the larger area in the lower Value and weaker Chroma and the smaller area in the higher Value and stronger Chroma."*



OSA radial scales of uniform
hue and chroma difference

across nine lightness levels, as projected in CIECAM with D65 illuminant; from Moroney (2003)

However, as the diagram (right) makes clear, Munsell's formula has an even simpler interpretation: for any small area, strongly chromatic color, the contrasting large area background should be very dull if it is light valued, and chromatic if it is very dark valued. In effect, a background can be "luminous" in lightness or in chroma, but not both.

Munsell's idea of color balance has widely influenced artists and designers in color selection. And his definition of "color strength" can be easily adapted to the OSA, CIELAB or CIECAM color spaces by correcting for the differences in the lightness and chroma metrics (for example, by dividing CIELAB chroma by 4 and CIELAB lightness by 10).

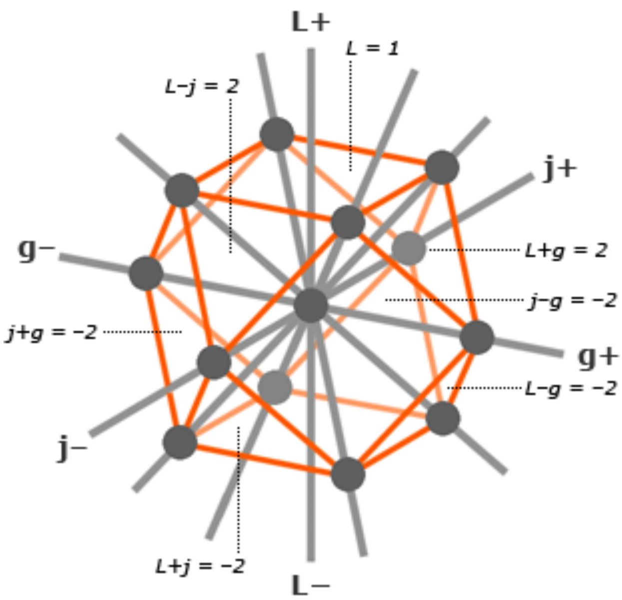
However, "color strength" has several flaws as a basis for determining color harmony. Because Munsell chroma has a greater numerical range than value, chroma tends to dominate the calculation of color strength. We've seen that the formula cannot specify how the "strength" should be divided between the color's value and chroma, so that both a pale light blue or an intense dark blue can be "harmonious" with the same intense orange yellow. And the examples in the diagram (above) suggest that other exceptions should be avoided, for example when one of the colors is a light valued gray.

7. Optical Society of America Uniform Color Scales. Perhaps the most methodologically rigorous color model developed in the 20th century was the set of uniform color scales developed from 1947 to 1977 by the Optical Society of America. I describe the development of this system on another page (http://www.handprint.com/HP/WCL/color7.html#OSA-UCS), and focus here on its application to color design.

The UCS color space is defined by three dimensions: a vertical **L+/L** or *light/dark* (lightness) dimension, and perpendicular to it the horizontal **j+/j** or *yellowness vs. blueness* dimension and the **g+/g** or *greenness vs. redness* dimension. The UCS dimensions are defined using the XYZ tristimulus values (http://www.handprint.com/HP/WCL/color6.html#transform) of the CIE 10° standard observer (http://www.handprint.com/HP/WCL /color6.html#fieldsize), as measured under the **D65** illuminant; it is therefore a *continuous* color space: any material color can be located within it.

The UCS project attempted to create a truly uniform spacing of color samples in all dimensions of a perceptual color space, measured from any color as the starting point. The UCS committee concluded that a truly uniform color space was impossible to implement in three dimensions, but it can be said in part to have failed that goal because it defined the goal so precisely.

Rather than work with the three colormaking dimensions as separate measurement scales, the committee defined the color space essentially as a large crystal. The spacing between "atoms" of color in the crystal the aim colors that exemplify the color space was rigorously dictated across all three dimensions simultaneously by the geometry of the cuboctahedron (diagram, below).



cuboctahedral geometry of the osa uniform color scales

lightness is measured on the **L+/L** dimension, yellow/blue on the **j+/j** dimension and red/green on the **g+/g** dimension; rhombohedral stacking of color "atoms" defines a total of seven unique cleavage planes through the color space (labeled on front planes), with additional two cleavage planes (not shown) defined perpendicular to the **j** and **g** dimensions. (**Note**: direction of **g+/g** dimension is reversed from standard orientation.)

This rhombohedral solid defines the type of stacking observed in the carbon atoms of a diamond crystal or in the oranges of a fruit stand display. The spacing in all directions is perfectly regular and maximally compact, creating a lattice for color measurement.

Following the crystallographic metaphor, the faces or facets of the cuboctahedron define seven **cleavage planes** through the color space, and joining cuboctahedrons vertically defines two more planes, perpendicular to the **j** and **g** dimensions. The edges of the cuboctahedron define the intersections between two cleavage planes, which form linear *uniform color scales*. Each cleavage plane contains all the aim colors whose **Ljg** coordinates satisfy one of the following nine formulas:

1. **L** = *constant;* **j,g** take any values
a plane perpendicular to the **L** *dimension and parallel to the* ***j*** *and* **g** *dimensions, forming a 1:1 square lattice of colors [see diagram, below]*

2. **j** = *constant;* **L,g** take any values
a plane perpendicular to the ***j*** *dimension and parallel to the* **L** *and* **g** *dimensions, forming a 1:1.4 rectangular lattice of colors [see diagram, below]*

3. **g** = *constant;* **L,j** take any values
a plane perpendicular to the **g** *dimension and parallel to the* **L** *and* ***j*** *dimensions, forming a 1:1.4 rectangular lattice of colors*

4. **L** + **j** = *constant;* **g** takes any values
a plane parallel to the **g** *dimension, at 55° to the* ***j*** *dimension and 35° to the* **L** *dimension, forming a 1:1 hexagonal lattice of colors*

5. **L** **j** = *constant;* **g** takes any values
a plane parallel to the **g** *dimension, at 55° to the* ***j*** *dimension and 35° to the* **L** *dimension, forming a 1:1 hexagonal lattice of colors [see diagram, below]*

6. **L** + **g** = *constant;* **j** takes any values
a plane parallel to the ***j*** *dimension, at 55° to the* **g** *dimension and 35° to the* **L** *dimension, forming a 1:1 hexagonal lattice of colors*

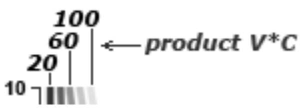
7. **L** **g** = *constant;* **j** takes any values
*a plane parallel to the **j** dimension, at 55° to the **g** dimension and 35° to the **L** dimension, forming a 1:1 hexagonal lattice of colors*

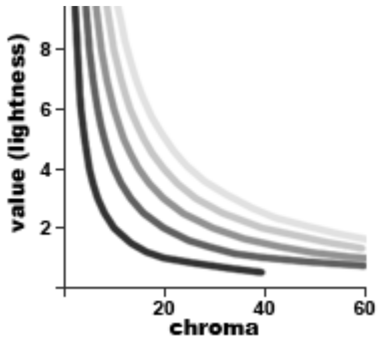
8. **j** + **g** = *constant;* **L** takes any values
*a plane parallel to the **L** dimension, at 45° to the **j** and **g** dimensions, forming a 1.4:1.4 diagonal square lattice of colors*

9. **j** **g** = *constant;* **L** takes any values
*a plane parallel to the **L** dimension, at 45° to the **j** and **g** dimensions, forming a 1.4:1.4 diagonal square lattice of colors*

where *constant* is any numerical value within the range of the UCS scale gamut (typically 12 to 12), a constant of zero selects the cleavage plane that passes through the mid valued gray (**L** = **j** = **g** = 0), and all planes defined using the same formula but different constants are parallel to each other within the color space.

Although the rhombohedral geometry makes color distance calculations explicit in three dimensions, it is intimidating to use for any other purpose. Aim colors are stacked in a square grid in the planes perpendicular to the **L** dimension, in a rectangular grid in the planes perpendicular to the **j** or **g** dimensions, in a diamond square grid in the planes diagonal to the **j** and **g** dimensions, and in a hexagonal grid in the four planes oblique to the **L** dimension; aim colors have odd number integer coordinates on the **j** and **g** dimensions in odd numbered lightness planes, and even number integer coordinates in even numbered lightness planes. This complexity, and the fact that the UCS formulas only function under a **D65** illuminant, are perhaps the main reasons why the UCS system is not more widely used, despite the fact that it is a continuous color space based on stimulus CIE XYZ values.

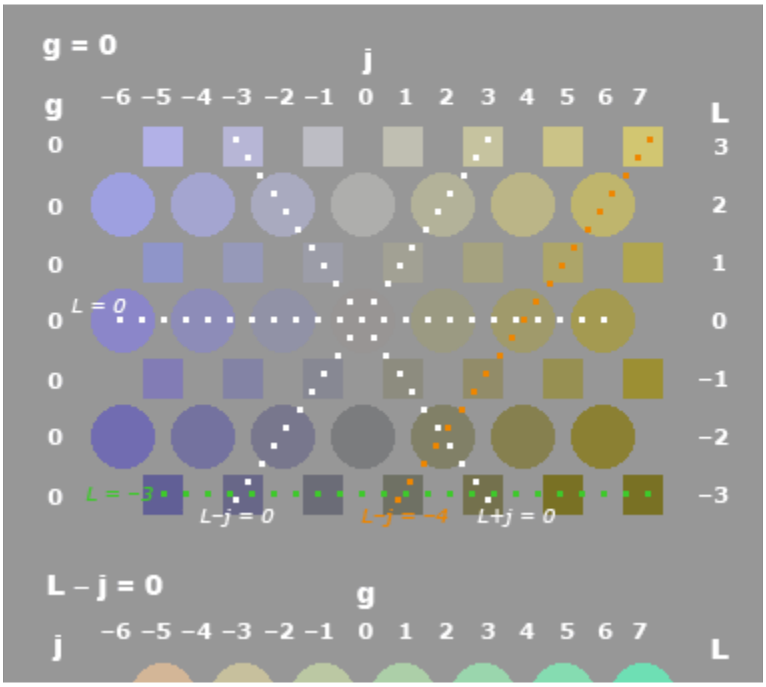


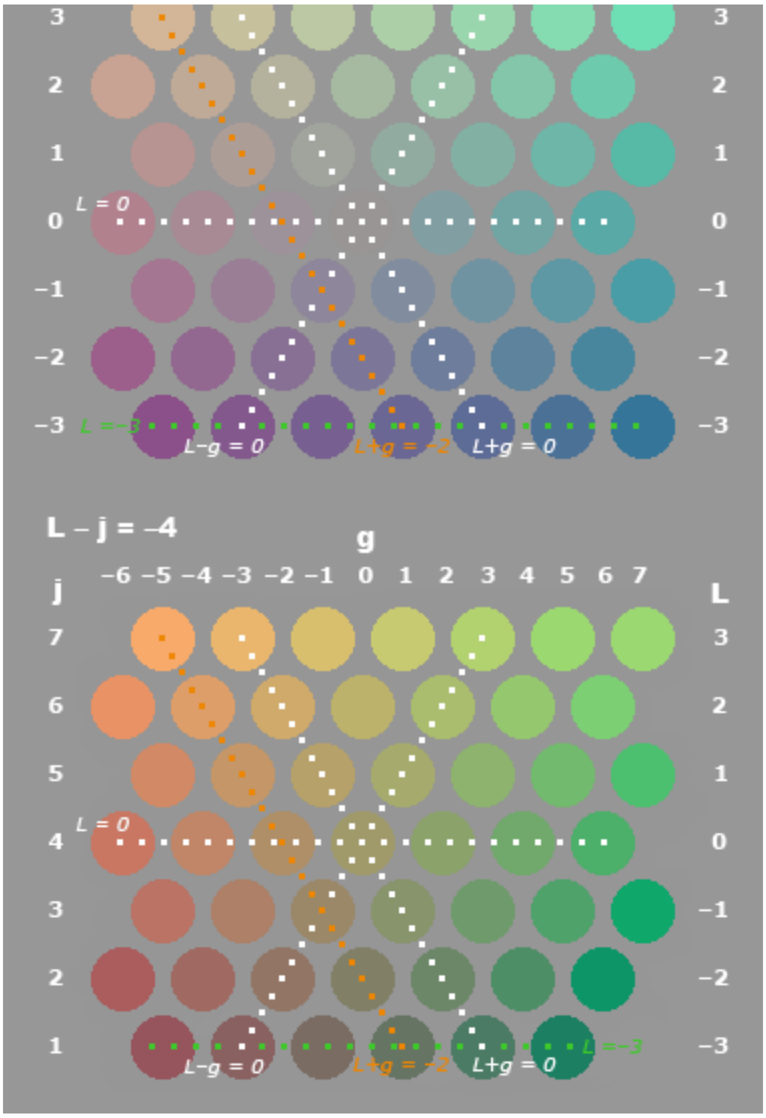


basic form of Munsell's balance equation

Unfortunately the OSA UCS exemplification as 558 color samples is no longer manufactured or available. To redress this in part, I've posted in this directory (http://www.handprint.com/HP/WCL/IMG/OSA/index.html) large format image files of the standard OSA full step aim colors, displayed as 111 cleavage planes with the correct rhombohedral spacing between color samples.

The diagram (below) shows four cleavage planes: **L** = **0** (square lattice), **g** = **0** (rectangular lattice) and **Lj** = **0** (hexagonal lattice), all centered on middle gray (**L** = **j** = **g** = **0**), and **Lj** = **4**, centered on a yellow ochre (**L** = **0, j** = **4, g** = **0**). Note the variation in the spacing of the lightness dimension.





four osa-ucs cleavage planes

top: square grid cleavage plane defined as **L** = **0**; **upper middle**: rectangular grid cleavage plane defined as **g** = **0** (smaller squares are aim colors interpolated from the half step set); **lower middle**: hexagonal grid cleavage plane defined as **Lj** = **0**; **bottom**: hexagonal grid cleavage plane defined as **Lj** = **4**; under D65 illuminant with gray background at **L*** = **62** (30% reflectance); XYZ color data from Wyszecki & Stiles (1982)

As the diagram illustrates, specific color scales can be defined within any cleavage plane by imposing a second formula from the set of nine, and all scales defined with the same formula (but different constants) will be parallel to each other, as shown for **L+g** = **0** and **L+g** = **2**, **Lj** = **0** and **Lj** = **4**, and **L** = **0** and **L** = **3**. In addition, scales defined with the same formula across different cleavage planes lie in their own common cleavage plane, so that (for example) the rows **L** = **0** in all three cleavage planes lie in the same **L** = **0** plane; and the scale **Lj** = **4** in the cleavage plane **L** = **0** corresponds to a vertical scale through the cleavage plane **Lj** = **4** at the value **g** = **0**. In all cases, every scale represents a series of color samples that are perceptually equally different from each other, and these units of perceptual difference are the same for all scales.

The point to all this is that the OSA UCS system has been offered as a useful tool in color design (http://www.babelcolor.com/download/AN-7%20The%20OSA%20UCS.pdf), under the claim that *every scale or cleavage plane* within the color space defines a perceptually "harmonious" assortment of colors. (Some writers claim more exactly that the color assortments are "well ordered" or "systematic".) In principle, designers select the specific cleavage plane that provides colors suitable for their design problem, then choose specific colors from that plane to create a .

Now, if we simply accept that claim, the question arises whether this procedure can be expressed as general principles of color selection. For example: harmonious selections must either lie in the same cleavage plane or along a line (color scale) defined by the intersection of two cleavage planes.

However, the OSA UCS planes and lines do not correspond in any direct way to differences in chroma, lightness or hue; instead, all three attributes vary in a way that preserves both equal perceptual spacing and linear relationships in the perceptual space. For example, the plane **Lj** = **4** (diagram, above) is centered on an ochre of CIELAB chroma 26, but the four corners of the color plane shown have chroma values of about 39 at the bottom and 55 at the top; chroma increases in concentric ellipses away from the central ochre.

This leads to the conclusion that **any color can be "harmonious" with any other color** and, because every color scale is found within two or more different cleavage planes, any *linear color series* can be harmonious with two or more *completely different* color palettes:

The OSA UCS system is fundamentally a *continuous* perceptual color space (any material color can be located within it), so its *color content* is equivalent to any other modern uniform color space.

The measurement units in the OSA UCS system were chosen arbitrarily; there is no reason why other measurement units cannot be used instead, and no reason why these cannot be contrived to represent an integer number of units between any two colors selected in advance. So *all possible color intervals* can be considered equally permissible.

The OSA UCS cleavage planes are determined by the rhombohedral geometry, but this was chosen to impose a measurement system, not to identify the planes of harmonious color variation. There is no reason why planes would appear displeasing if defined at alternative angles or measurement intervals between the existing cleavage planes (for example, **L(j/2)** = **-4.3**). Therefore *all possible plane and scale orientations* can be considered equally harmonious or useful.

In other words, in any perceptual color space, we can define a plane containing any three colors chosen at random, then divide up the plane into color intervals or color scales using any convenient measurement intervals.

The OSA UCS system frees us from the requirement of holding lightness, hue or chroma constant to create color harmony, as earlier approaches have done. Instead, we relinquish the colormaking attributes as the essential dimensions of color design, and rely instead on color assortments defined by any plane in any orientation to the **L**, **j** and **g** (or **L**, **a**, **b** or **J**, **a**, **b**) dimensions of the color space.

This plane defines the gradations on lightness, chroma and hue necessary to produce harmony in the color assortment.

The OSA UCS system therefore promotes a single color design principle: the euclidean formula for a plane in three dimensions. (The linear color scales are the intersection between two color planes.) We can stipulate this as measured within either OSA-UCS, CIELAB or CIECAM as:

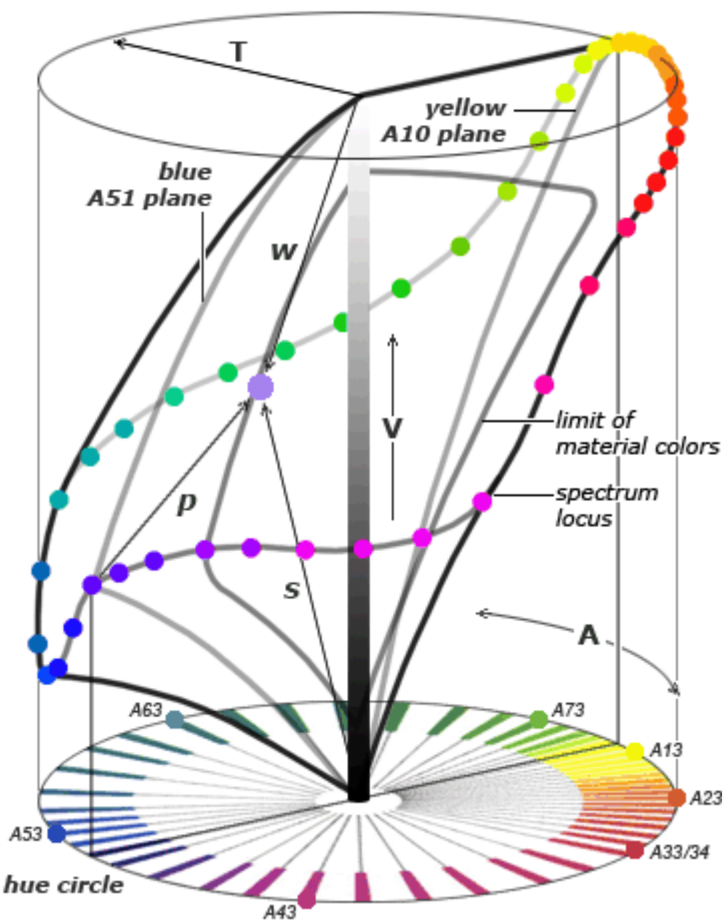
$s_L L + s_a a + s_b b$ = constant

where **L**, **a** and **b** are just the perpendicular dimensions of the perceptual color space; the weights $\mathbf{s_L}$, $\mathbf{s_a}$ and $\mathbf{s_b}$ are slope parameters for the three perceptual dimensions that determine the orientation of the plane (at least one of which must not equal zero); and the constant defines the shortest distance between the plane and the mid valued gray. In this equation the dimension weight $\mathbf{s_x}$ equals zero if the plane is parallel to dimension **x**.

8. Coloroid Hybrid Harmonies. An apparently hybrid model is the Coloroid Color Space (http://heja.szif.hu/ARC/ARC-030520-A/arc030520a.pdf) first published in 1980 by Antal Nemcsics and created primarily for architects and "visual constructors" (?). I've introduced this model as an illustration of how you should approach the conceptual analysis of any color space.

In the Coloroid system, colors are specified or notated according to their location on 48 planes of constant hue (**A**), colors on each plane arranged according to their "saturation" (**T**) and "luminosity" or lightness (**V**), the colormaking system typical of a perceptual color space. The hue circle divided into seven basic hue categories: yellow, orange, red, violet/purple, blue, cold green and warm green; each category is subdivided into seven hue subcategories (except red, which is subdivided into six), to produce 48 basic color planes.

However, inspection shows that the Coloroid "saturation" is actually or chromatic component, and colors are equivalently specified according to their hue content (**p**), white content (**w**) and black content (**s**), separate components that always sum to 1, which is the specification system for a colorant color space (diagram, below). On first encounter, then, we might be unsure whether this is a perceptual or colorant color space.



the coloroid color space

A denotes the hue or dominant wavelength of a color; **T** denotes the hue purity of a color; **V** denotes the luminosity or brightness of a color; all colors can be defined equivalently as components of pure hue (**p**), white (**w**) and black (**s**)

However, all the diagnostic clues are here to show that the Coloroid aims to be a uniform perceptual color space. The model is defined using a cylindrical geometry, and the enclosed color solid is not geometrically regular. Hues are not defined as proportional mixtures of any set of "primary" colors but in terms of the CIE XYZ stimulus specifications or as the matching dominant hue wavelength in the 1931 CIE xy chromaticity diagram. For example, yellow A10 matches wavelength *567,* and blue A51, an extraspectral hue of blue violet, matches the mixture of wavelength *450* with a small quantity of wavelength *625*. Finally, the 48 *hue planes* are not equally spaced, as they would be using incremental proportions of primary hues, but rather are spaced according to *perceived* equal hue differences, which means that there are 23 hue planes in the quadrant A72 to A33 (yellow green to red), but only eleven hue planes in the complementary quadrant A45 to A61 (red violet to blue green).

In the technical documentation, Nemcsics describes Coloroid as *"a compromise of principles of uniformity in regard to color difference and color harmony, as well as ease of mapping into the CIE colorimetric space."* Color differences or increments of color change within the system represent *"an aesthetically uniform system, in which scales of hue, saturation, and lightness appear to change uniformly over their entire length, when viewed as a whole. This is not the same as perceptually uniform in the sense of even intervals of small color differences."*

As this is essentially an "aesthetic" color space designed for use in architecture and design, the Coloroid documentation specifies schemes for producing harmonious color selections. Color combinations are deemed "harmonic" or harmonious when the colors:

have the same hue and chroma, and vary on lightness in steps of equal perceptual difference (arithmetical) or in steps of increasing perceptual difference (geometrical)

have the same hue and lightness, and vary in chroma in either an arithmetical or geometrical series have the same hue, and vary by equal amounts on both lightness and chroma in either an arithmetical or geometrical progression, and additionally vary along any line parallel with this progression in the same hue plane

Any of these progressions can be distributed over "trichrome" hues, or the central hue in any of the basic hue categories (indicated in the diagram, above) paired with the extreme hues in the same hue category, with the central hue of the corresponding complementary hue (equivalent to a split complementary (http://www.handprint.com/HP/WCL/tech13.html#splitcomplementary) color harmony)

any two hues selected from any of the above series constitute a dichrome hue harmony, even when the basic hue is omitted.

These color combination formulas are indistinguishable in effect from the schemes previously proposed by Chevreul, Birren or Munsell, and are more limited than the complex system of seven harmonious scales defined around any given anchor color proposed in the 1970's as the Optical Society of America's uniform color scales (http://www.handprint.com/HP/WCL/color7.html#OSA-UCS).

We have seemingly reached the point where refinements or innovations in the specification of perceptual color spaces do not produce any increase in our understanding or definition of color harmony.

(http://www.handprint.com/HP/WCL/wtech.html)

handprint.com (http://www.handprint.com/HP/WCL/tech13.html)