handprint : modern color theory (concepts)

handprint.com (http://www.handprint.com/HP/WCL/color18a.html)

modern color theory (concepts)

This page introduces the conceptual basis of artists' "color theory" the traditional body of lore applied by painters and photographers to the design and creation of images. The addition of "modern" indicates that I compare the traditional (and still popular) tenets of color theory to the answers provided by modern color science.

The companion page on modern color theory (applications) (http://www.handprint.com/HP/WCL/color18b.html) provides practical insights into pigment attributes, paint formulation, the behavior of color mixtures, palette design and the principles of color contrast the practical knowledge necessary to put color theory concepts to work.

This page is a condensed summary of the content included in my pages on color science (http://www.handprint.com/LS/CVS/color.html) and artistic color theory (http://www.handprint.com/HP/WCL/wcolor.html).

Before we start: **what is color theory *for?*** Historically, its teaching literature has claimed to provide artists with four broad of knowledge:

Insight into **subtractive color mixing** with paints, inks or dyes.

Prediction of the **color context effects** produced in colors that are viewed in contrasting surrounds or visual patterns.

Guidance in the selection of **color schemes** or color design used in paintings, furnishings and architectural interiors.

Identification of the relationship between individual colors and ideas or emotions usually called **color symbolism**.

An exploration of the issues important to color design is provided on the page color harmony & contrast (http://www.handprint.com/HP/WCL/color17.html).

Traditional color theory has implicitly been about , my term for color treated in the abstract rather than as physical paints or . Conceptual color is divorced from materials or colorants, independent of viewing context, and mixes according to idealized rules. In both this page and the next, I emphasize the differences between conceptual and material color, as each influences the visual color we experience through our eyes.

talking about color

"When I use a word," Humpty Dumpty said, in a rather scornful tone, "it means just what I choose it to mean neither more nor less."

Lewis Carroll, *Through the Looking Glass*

When you consider that painters are in the business of manipulating color, it is surprising that very few artists can describe color clearly. In fact, a muddled color lexicon is one of the hallmarks of "color theory" past and of color theory even today. Betty Edwards (http://www.handprint.com/HP/WCL/book3.html#edwards), in her recent *Color: A Course In Mastering the Art of Mixing Colors* (2006), is an enthusiastic contributor to this carefree performance tradition.

Why do artists need to talk about color accurately and clearly? Simply because how we talk about color affects how we understand color, and how we understand color affects how we identify, manipulate and use colors in painting.

Four Kinds of Color. One of the difficulties in talking about color is that color seems to exist in several different forms. Indeed, Paul Green-Armytage, in one of the many web pages now lost to oblivion, claimed to identify seven types of color. For the artist, however, it is helpful to discriminate between four types of color.

1. There are four fundamental categories of color: material color, radiant color, visual color, and conceptual color.

material color is the physical pigment, dye, filter, pigmented or dyed material, or light source that originates the experience of color. Artists very often speak of "mixing different colors" or of "choosing colors for a painting", and what they are talking about is material color (pigments).

Material color is the sense in which we equate color with the physical world, and speak of a pigment as *cadmium orange* or *phthalo green,* or a dye as *yellow number two,* or talk about a *white shirt* or a *red sky*.

radiant 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, or photographic emulsion. This defines color very narrowly, as a *physical stimulus* independent of any other lights or surfaces around it.

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

Radiant color is not equivalent to the material color of a pigment, dye or filter: we never experience material color directly, but only through the radiant color it creates. In addition, a pigment's radiant color changes as it is diluted, mixed with different vehicles, applied to different surfaces, or viewed from different angles or under different types of light. The same "color" (material color) can produce an enormous range of different "colors" (radiant colors).

visual color is the perception of radiant color in a specific viewing context usually as a physical surface in a specific place under a specific intensity and color of illumination.

Visual color literally does not exist outside individual consciousness. 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 radiant color can appear as very different visual colors, depending on the intensity of the light and the context in which 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 radiant 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 material 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 material or radiant color is surrounded by 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 radiant color (the) into a color appearance specification on the three *colormaking attributes* (discussed below); or by finding the best visual match between the visual color and a material color sample published as a standard *color atlas*; or by matching the material color to a colorant mixture 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 the material or radiant stimulus 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 material, radiant 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 social framework of talking about color, but unreliable as the basis to specify color for any specific purpose.

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

color theory

modern color theory (applications) (http://www.handprint.com/HP/WCL/color18b.html)

summary of modern color theory (http://www.handprint.com/HP/WCL/princsum.html)

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

The Colormaking Attributes. A standard, unambiguous language for visual color description is an innovation of 19th century color scientists. And the foundation of this color language is the idea of a "color container" or *color space*.

2. Vision scientists have identified three colormaking attributes (http://www.handprint.com/HP/WCL/color3.html#colormaking) *lightness, hue* and *hue purity* that are sufficient to precisely specify any visual color.

(*Brightness* replaces lightness when we want to describe lights or the light falling on or reflected from surfaces, and *colorfulness* replaces chroma when we want to describe lights or surfaces in comparison to an ideal or imaginary, "pure" hue.)

Let's consider each colormaking attribute separately, to understand how the attributes arise in radiant colors, and how we should describe (as conceptual colors) the color perceptions (the visual colors) they produce.

Brightness/Lightness. The visually most important (http://www.handprint.com/HP/WCL/color11.html#dominance) colormaking attribute is the **light or dark of a color** as it appears in emitted or reflected light. This is perceived in two distinct ways:

3. Brightness is the sensation of light emitted or reflected from an object that is greater than the light reflected from a matte "white" surface under the same illumination.

Brightness is only weakly correlated with the actual luminance (http://www.handprint.com/HP/WCL/color3.html#luminance) of an object. For example, car headlights appear painfully bright at night, but in noon daylight they may be barely visible. The luminance is the same, but the apparent brightness varies with context.

4. Lightness is the sensation of light emitted or reflected from a surface as a proportion of the light emitted or reflected from the brightest surface (or a matte "white" surface) under the same illumination.

Lightness is strongly correlated with the overall reflectance (http://www.handprint.com/HP/WCL/color3.html#reflectance) (*luminance factor* or *albedo*) of surfaces, provided that different surfaces are in view at the same time and all surfaces are illuminated within the same light environment.

Artists commonly use the term **value** to refer to lightness, a term made standard through the Munsell Color System (http://www.handprint.com/HP/WCL/color7.html#MUNSELL).

The example below shows variations in the lightness of a blue hue with low chroma.

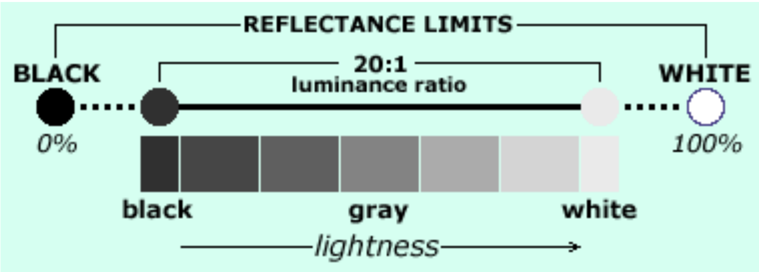
differences in lightness or value

hue and chroma held constant

Extremes of lightness or value are described as *dark* or *black* up to *light* or *white;* for self luminous areas (lights) the extremes of brightness are described as *faint* or *dim* up to *brilliant* or *bright*.

Perceptions of lightness form a continuous achromatic series, called a of values, extending from perceptual black through grays of increasing lightness to perceptual white. All colors, disregarding their hue and chroma, can be matched to a step on this lightness scale, either visually or by measuring their reflectance with a spectrophotometer.

In technical color models, lightness (http://www.handprint.com/HP/WCL/pigmt8.html#valrange) is measured on a scale from 0 (black) to 100 (white); painters and photographers use printed gray scales that may contain anywhere from 5 to 20 gray scale steps. Different naming or numbering categories are used in these systems; see for example my Handprint lightness categories (http://www.handprint.com/HP/WCL/color13.html#lightnesscategories).



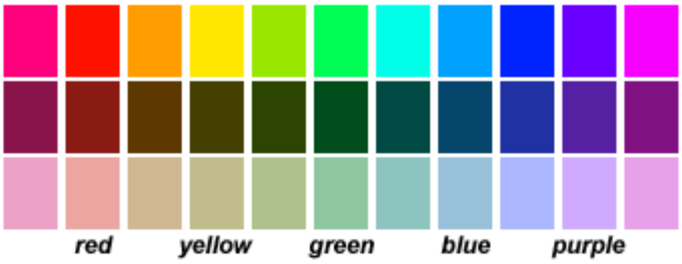
perceptions of lightness form a gray scale that is much smaller than physical reflectance limits

The physical basis of lightness is essentially the overall proportion of light shining on a surface that is reflected from the surface: dark surfaces reflect very little light, and pale or white surfaces reflect a lot of light.

However this does not mean that our perception of lightness is fixed on extreme physical reflectance values of almost 0% ("pure black") and 100% ("pure white"). Instead, the *perceptual* white and black values are anchored (http://www.handprint.com/HP/WCL/color4.html#anchoring) on the most extreme light and dark surfaces within the field of view and by remembering how familiar surfaces look under normal light. These relative contrasts can define a complete range of grays in surface luminances that do not vary by more than 20 to 1. In fact, we typically perceive as "black" surfaces that reflect as much as 10% of the light falling on them, and as "white" surfaces that reflect only 90% of the light a reflectance ratio of just 9 to 1.

In addition, judgments of light and dark can change when surface comparisons change: think of laying an old white sheet you consider "white" against a brand new white sheet. Lightness is affected by the among all visible surfaces. Changes in illumination have less impact on perceived lightness, provided the same surface contrasts are in view or the surfaces are already familiar.

Hue. This is the most familiar color attribute, the one that answers the question, *what color is it?* The example below shows several different hues.



differences in hue

colors in the same column are the same hue: (top row) hues at maximum chroma; (middle & bottom rows) dark and light hues, with chroma and lightness held constant (colors of equal nuance) in each row

5. Hue is the attribute of color matched by a single wavelength of light or by a mixture of "violet" and "red" wavelengths of light.

Hues arise because the light incident on a surface is reflected unequally at different wavelengths. The eye combines these different wavelengths into a single hue perception. This hue can usually be matched by the color of a single wavelength of light, called the **dominant wavelength** of the hue, notated as the wavelength number, e.g. a pure yellow is indicated by the wavelength number *575*. Hues that do not appear in the spectrum are matched by a mixture of two wavelengths of light, one violet and one red. As these two wavelength mixtures or **extraspectral hues** are awkward to specify for technical reasons, they are usually denoted by the wavelength number of the hue directly opposite on the hue circle: thus an extraspectral magenta is notated by its complementary "green" wavelength, *c560*.

The artistic description of hue departs from everyday color description in two ways:

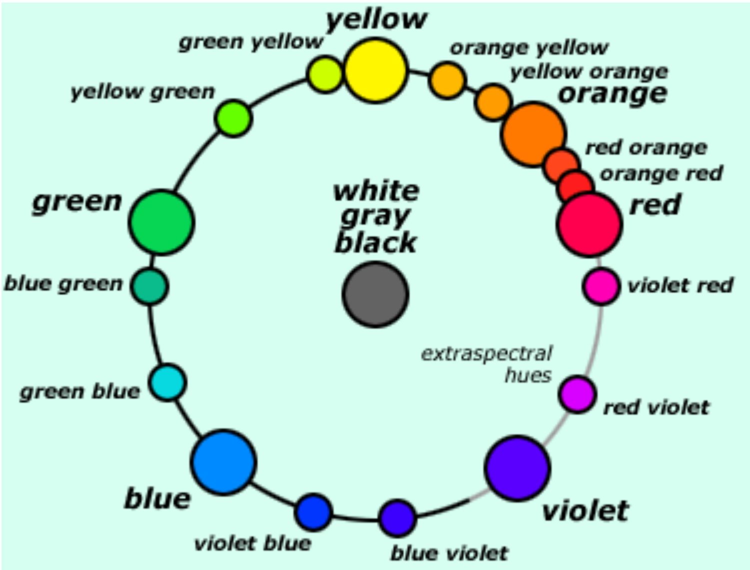
Hue names are limited to six: the spectrum hues (http://www.handprint.com/HP/WCL/color13.html#names) *red, orange, yellow, green, blue* and the extraspectral hue (http://www.handprint.com/HP/WCL/color2.html#extraspectral) *violet* (or *purple,* which I use to describe a dark violet). Note that the extraspectral range includes many hues commonly labeled *red* (diagram, right).

Dull colors are named as spectrum hues. The unique names for dull or muted colors such as *brown, maroon, pink, tan, gold, russet, olive* and so forth do not describe spectral colors, and this means they are not hue names, even though they may be appropriate informal replies to the question, *what color is it?*

For the spectral wavelength and paint pigment hues corresponding to the major hue categories, see my Handprint hue categories (http://www.handprint.com/HP/WCL/color13.html#huecategories).

Spectral hues blend continuously, each into its neighbors, to form a circle of hues, in spectral order from red to violet. Extraspectral hues (reds and violets mixed from a blend of "red" and "violet" light) close the hue circle. Hue only specifies the location of a color around the circumference of this circle, usually specified as an angle (the hue angle (http://www.handprint.com/HP/WCL/pigmt8.html#hueangle)) measured from an arbitrary starting hue (usually red or yellow).

Blends of the basic hues are named with two neighbor hue names, following the rule **the tinting hue name precedes the dominant hue name**, as adjective before noun. Thus *red orange* is an orange leaning toward red, *blue violet* is a violet leaning toward blue, and so on. This creates six basic and twelve compound hue categories. These are illustrated below, in the approximate spacing that the hues display in a .



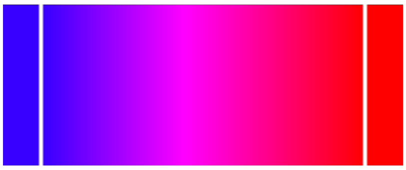
perceptions of spectral hues form a hue circle

six basic hues and twelve compound hues, with achromatic white, gray or black

This hue circle may seem erratic, but in fact the locations of *red, yellow, green, blue* and *violet* are equally spaced around the hue circle, and match up with the five basic hue categories of the Munsell Color System (http://www.handprint.com/HP/WCL/color7.html#MUNSELL) (**5R**, **5Y**, **5G**, **5B** and **5P**); *orange* has been added to discriminate among the very large number of artists' pigments (http://www.handprint.com/HP/WCL/palette1.html#greenyellow) in the yellow to red hues. (Exemplars of the hue categories are .)

Some blended hues are more familiar as unique color names (especially *magenta* for *violet red* and *cyan* for *green blue*), but other names for compound hues are unfamiliar or infrequently used (*chartreuse* for *yellow green*). Naming hues with matching pigment names ("ultramarine" for *violet blue*, "vermilion" for *orange red*) should be avoided, to prevent confusion between colors and paints.

Achromatic colors, including *white, gray* or *black,* are not hue categories, but are used to describe colors of paint (*davy's gray*), gradations in lightness (a *dark gray value*), dull color appearance (a *gray green*), or even levels of luminance (a *gray day,* a *black night*).



the extraspectral hues

these include all hues between blue violet (left) and orange red (right)

To assist you in learning the hue categories, this site uses a palette scheme icon (right) to identify pigment categories and to identify artist palette paint selections (http://www.handprint.com/HP/WCL/paletfs.html). Click on the icon anywhere it appears to view the key to the palette scheme (http://www.handprint.com/HP/WCL/colormap.html); click on any hue marker in the palette scheme to see a listing of watercolor pigments currently available in that hue category (as listed on the complete palette (http://www.handprint.com/HP/WCL/palette1.html) page).

An artist's color mixing skill is greatly aided by learning the correct hue designations for dull colors. "Brown" for example is actually a near neutral, dark valued orange with a dominant wavelength around 610 nm. Of course you would not normally describe your coffee as *dark orange*. But accurate hue naming makes it clear how a color should be mixed with paints and how a color is likely to change when in shadow.

For example, *red orange* can be mixed as orange paint tinted with some red paint; *dark orange* (brown) can be mixed by darkening an orange paint with black; and an orange surface in deep shadow shoud be painted with brown paint.

Hue Purity. The third colormaking attribute represents the quality of color commonly called chroma or saturation.

6. Hue purity is the concentration or intensity of hue independent of its luminance or lightness, commonly termed the *colorfulness, chroma* or *saturation* of a color.

The example below shows variations in the chroma of a green and red at constant hue and lightness.

differences in chroma (saturation)

hue and lightness held constant

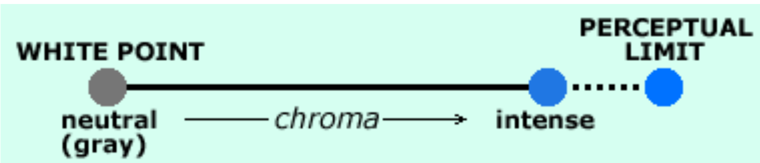
This basic attribute of "hue purity" has gone by many names *Sättigung, colorfulness, chromaticness, chroma, saturation, excitation purity, colorimetric purity, chromatic content, brilliance* each definition anchored to a specific stimulus attribute or color comparison. Artists can use either **chroma** or **saturation** to describe hue purity without worrying about the technical distinction between the two terms:

Chroma was first used by Albert Munsell in his Munsell Color System (http://www.handprint.com/HP/WCL/color7.html#MUNSELL) (1915), and the term now has widespread application in technical color systems.

Saturation goes back to 19th century color science; *saturated color* is recognized in common speech and conveys the juicy metaphor of a surface *soaked* in pure hue.

Chroma or saturation varies from *dull* for weakly tinted sensations to *intense* for pure hue sensations. The terms **neutral** or **achromatic** apply to colorless (white, gray or black) surfaces. (Note that *lights* can never appear gray or black, but only as a bright or dim.) For a chroma naming system and visual examples, see my Handprint chroma/saturation categories (http://www.handprint.com/HP/WCL/color13.html#chromacategories).

In visual colors (and by extension, in the material colors that stimulate the visual colors), hue purity is defined as the **proportion of black, gray or white in a color** relative to the proportion of "pure hue" (in materials, the pigment or dye) in the color. Colors with low chroma or saturation appear very similar to a white, gray or black. The perception of chroma forms a scale anchored in achromatic colors at one end and extending to the most chromatic stimulus at the other. In modern color models, chroma is measured from zero (achromatic) to a maximum value at the .



perceptions of chroma are anchored on achromatic surfaces matching the white point

The perception of achromatic or zero chroma surfaces is strongly affected by the chromaticity (the combination of hue and hue purity) of the illumination. Our visual system naturally adapts to weakly tinted illumination so that it appears as "white" or achromatic light. It is then the **white point** or standard of zero chroma. Any surface tinted with the same hue will appear achromatic (white or gray), but this judgment will change if the color of the illumination changes.

There are two language pitfalls to avoid when talking about gradations in chroma or saturation. The first involves color adjectives that can mean either *quantity of light* or *concentration of color* these include *intense, brilliant, shining, glowing, bright* or *luminous*. If you say the setting sun is a *more brilliant red* than an apple, it is unclear whether you are pointing at *brightness* or *saturation* or both.

The same pitfall involves adjectives borrowed from the material connotations of *purity* such as *pure, clean, concentrated, fresh* or *strong* and their antonyms *impure, dirty, diluted, faded* and *weak*. Here the ambiguity is material a faded color may be inherently drab, or mixed with white; a diluted color may be inherently dull, or diluted with water. These terms also introduce a judgmental tone that is pointless when talking about color.

Warm and **Cool**. Trades that use color for artistic, design or decorative purposes commonly use two terms to denote a "metacomplementary" hue contrast across the hue circle.

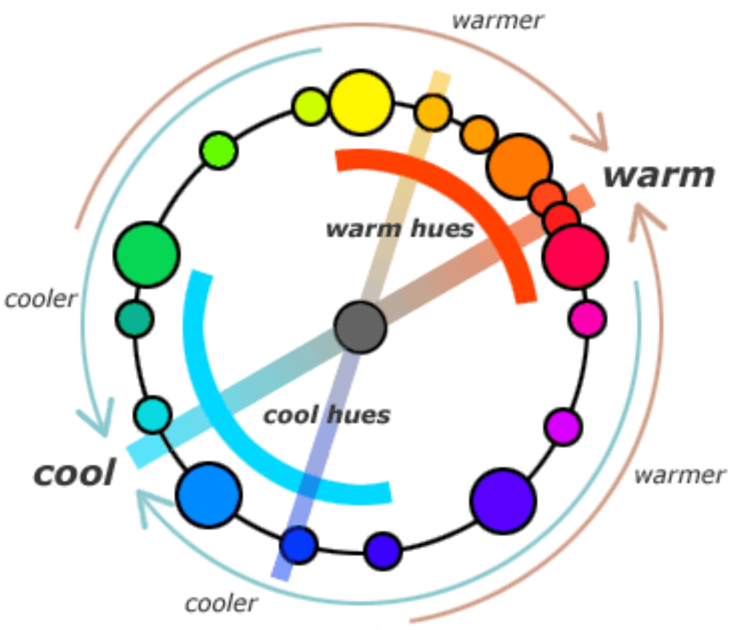
7. Artists use *warm* to refer to red, orange and yellow hues, and *cool* to refer to blue green and blue hues.

These terms are used to describe hue contrasts (http://www.handprint.com/HP/WCL/color12.html#warmcool) in two different ways:

(1) as a *fundamental* contrast between hues that are yellow, orange, red without a tint of green or blue (*warm*) as opposed to hues from green to blue without a tint of yellow or red (*cool*).

(2) as a *relative* contrast between two similar or analogous hues, where one of the hues appears to contain more yellow or red (is *warmer*), or more green or blue (is *cooler*), than the other.

The fundamental warm/cool contrast is typically anchored on the hues *red orange* and *green blue,* or more simply between *orange* and *blue*. Either way, the warm/cool axis is not placed through the centers of the warm and cool hue groups, because the spacing of the warm and cool hues is unequal (although each group contains about a half dozen hue categories).



the warm/cool contrast

Most color theory texts categorize greens and purples as either warm or cool. This is inaccurate. The hues from green yellow to green, and from violet blue to violet red, are neither warm nor cool. In these hues blue and red, or yellow and green, visibly mix, so violet and yellow green are warm/cool hybrids. Note also that the complementary contrast between yellow green and violet is not as strident as the contrast between red and green or yellow and violet blue.

However, a minority of artists anchor the contrast on *orange yellow* and *violet blue:*

in that case orange is warmer than red, and blue is cooler than blue green. This usage corresponds to the contrast between *optimal orange* (the color produced by all long wavelength light above 570 nm) and *optimal blue* (the color produced by all short wavelength light below 485 nm), as identified in the synthesis of color vision (http://www.handprint.com/HP/WCL/color19.html#sixcolors). These colors are most closely matched by the pigments nickel dioxine yellow (PY153 (http://www.handprint.com/HP/WCL/watery.html#PY153)) and ultramarine blue (PB29 (http://www.handprint.com/HP/WCL/waterb.html#PB29)). Visually, this preference is strongly justified by the importance of the yellow/blue axis as the major dimension of variation in the chromaticity of natural light (http://www.handprint.com/HP/WCL/color12.html#wcequalsyb) and in particular in the atmospheric and diurnal variations of landscape light (http://www.handprint.com/HP/WCL/color12.html#colorlight).

Many artists also use *warm* and *cool* to describe a relative *chroma contrast* between warm or cool hues: brown is warmer than gray but cooler than red orange, and iron blue is warmer than cobalt blue but cooler than gray. These distinctions are especially useful to analyze subtractive color mixtures, because blue can be made into indigo, or gray into brown, by mixing them with red or orange paint (or colored light), and red orange can be made into brown, and gray into indigo, by mixing with blue paint (or colored light). This highlights the benefit, mentioned in the labeling of hue categories (above), of matching color labeling to the logic of color mixtures in paints.

(http://www.handprint.com/HP/WCL/colormap.html) the palette scheme used throughout this site

click on the icon to go to the key to the palette scheme

Other Material Color Terms. Although the colormaking attributes are necessary to specify a visual color, they are not sufficient to describe certain physical attributes of a colored substance.

8. Physical or surface qualities of color materials are described with the terms *gloss, translucency* or *transparency, fluorescence,* and *iridescence* or *pearlescence*.

These additional color attributes are defined as follows:

Gloss. All materials reflect some light from their surfaces much as a sheet of glass does. This light does not get absorbed or reflected by any colorant within the material, so the reflected light is effectively "white". *High gloss* materials have the property of reflecting most or nearly all of this "white" light in one direction, which produces a *highlight* or image of the light source on the surface. *Low gloss* materials reflect this "white" light in all directions, producing a nonreflective, *matte* or "flat" surface color. In matte surfaces we always see some of this diffuse white light mixed into the surface color, so a material with a matte surface always appears both duller and lighter than the same material with a gloss finish.

Translucency/Transparency. Many materials allow light to penetrate below the surface, or even pass through an object entirely: they *transmit* light. If a material transmits so much light that a bright, clear image can be seen through it, the material is *transparent*. If the material transmits light only as a diffuse glow or vague image, then it is *translucent*. If a material transmits no light, it is *opaque*. (Note that paint attributes are described differently, using the separate concepts and or hiding.)

Fluorescence. Surfaces seem to glow or fluoresce if they appear to emit more light than is shining on them. This usually occurs because the substance absorbs light in the invisible short (ultraviolet) wavelengths, then emits the energy as light in the visible wavelengths, or because it absorbs light in the bright ("green") wavelengths, and emits it in the dim ("red") wavelengths.

Iridescence and **Pearlescence**. These terms describe the appearance of different colors in the same spatial location, or colors that change depending on the angle between the object and light or the object and our point of view. Both are usually produced by some form of diffraction or refraction (http://www.handprint.com/HP/WCL/color10.html#refraction) which is the production of spectral hues by reflection from a complex surface (as from a compact disc, or a film of grease on water) or by optical bending within a transparent material (as by a lens or prism).

A Basic Color Vocabulary. The colormaking attributes provide the artist with a clear and simple way to talk and think about color. Every artist must understand how to describe any color in terms of:

relative luminance, which is **lightness** in surfaces (from *light* to *dark* for chromatic colors and *white* to *black* for achromatic colors), and **brightness** in lights (from *bright* to *dim,* whether chromatic or not).

hue as either *red, orange, yellow, green, blue* or *violet;* or any compound of two adjacent hue words, with the dominant hue named after the subordinate hue (as noun after adjective): *red violet* is a violet tinted with some red.

hue purity as either *chroma* or *saturation* and using the adjectives *near neutral* or *dull* (for low chroma color) and *intense* (for high or maximum chroma color).

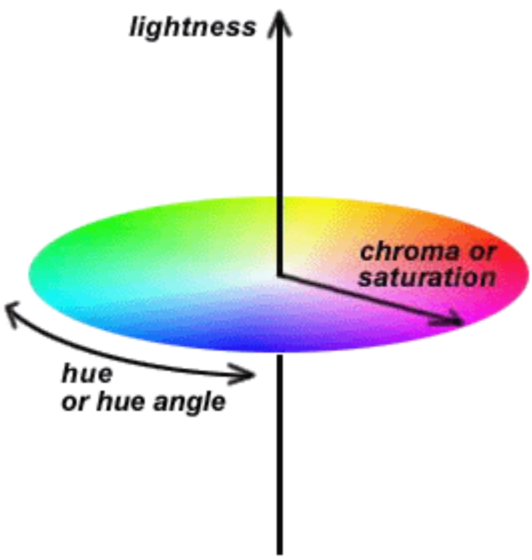
warm vs. cool *warm* colors are hues of yellow, orange and red that contain no visible blue or green; *cool* colors are hues of blue and green that contain no visible yellow or red; *warmer* colors are closer to red orange, and *cooler* colors are closer to green blue.

physical attributes, either of the surface texture or of the internal transmittance and/or refraction of light, can be described with terms such as *gloss, transparency, translucency, pearlescence, iridescence* and *fluorescence*.

The Color Space. The colormaking attributes are useful because they correspond to the visually most important differences among colors, and because they can be arranged to define a three dimensional **color space**, the geometrical framework for all modern color models (http://www.handprint.com/HP/WCL/color7.html).

9. All colors can be uniquely identified and related to each other as locations within a *color space,* specified by the dimensions of *brightness/lightness, hue* and *hue purity*.

The figure below shows how a color space is put together.



the geometry of colormaking attributes

in a modern color space

The vertical dimension is the *lightness or value* of a color; by itself, this dimension defines a **gray scale** of values from black to white. The circumference of the horizontal disk, perpendicular to the lightness dimension, is the *hue* of a color; this defines a **hue circle** that places hues in their spectrum order. The lateral distance or radius on this disk, measured from the center outward, is the *hue purity* of a color, usually stated as its relative *chroma* or absolute *colorfulness*.

You will find color models in many different shapes, proposed by different color experts (http://www.colorcube.com/articles/models/model.htm). However, modern color spaces are generally of two types (diagram, right):

10. Modern color spaces are of two types: a *colorant* space is based on mixtures of real or imaginary "primary" colors, and a *perceptual* color space is based on the visual colormaking attributes.

The *colorant color spaces* (for example, the Swedish Natural Color System (http://www.handprint.com/HP/WCL/color7.html#NCSmodel) or the RGB color space (http://en.wikipedia.org/wiki/RGB_color_space)) all stipulate that (1) the color space will have a simple geometrical form; (2) the geometrical distances between three or four "primary" colors are equal; (3) colors are defined as the proportional mixture of primary colors necessary to match the color.

The *perceptual color spaces,* (for example, the recent CIE models CIELAB or CIECAM, Manfred Richter's DIN, the OSA UCS system) do not impose colorant boundaries or a specific geometrical shape on the distribution of colors. They only require the hue circle and chroma to be perpendicular to the lightness dimension: colors are located by measuring their actual lightness, hue and hue purity.

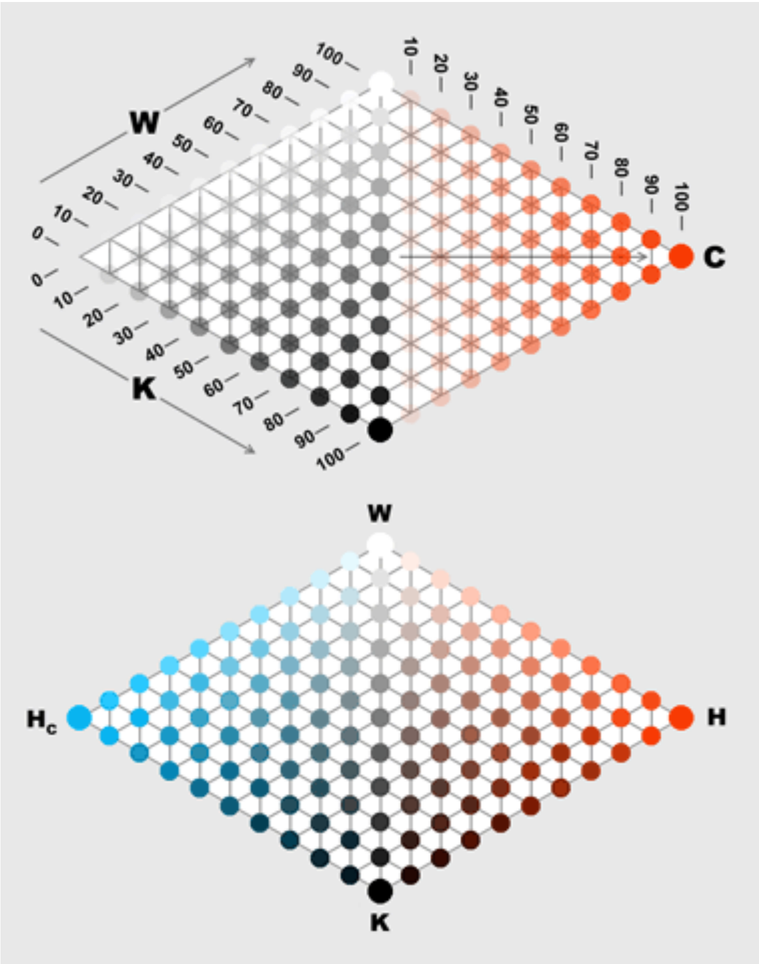
Peceptual color spaces describe all visual colors, either of light or of materials or both, and are standard in color vision research. Colorant color models are not visual color spaces, because lightness/brightness, hue and hue purity are not defined within them. Instead they are geometrically simplified diagrams of the colors produced by all possible mixture proportions among the primary colorants used in subtractive (paints, inks) or additive (phosphors, lights) color reproduction media.

For the purposes of the study of color harmony and contrast, it is useful to understand all color models or color spaces can be categorized into one of two categories *colorant spaces* and *perceptual spaces*:

two types of color space *Colorant SpacesPerceptual Spaces* Boundariesmixture gamutperceptual limits *additive Luminance***BrightnessBrightness** *Hue***Primary LightsOpponent Dimensions** *Hue Purity***SaturationChroma** *Examples*CIE Yxy
RGBCIELUV
CIECAM (with Q) *subtractive Luminance***BlackLightness** *Hue***Pure Pigment(s)Opponent Dimensions** *Hue Purity***WhiteChroma** *Examples*NCS, DIN,
CYMKCIELAB
CIECAM (with J)

The fundamental difference is whether the color model first chooses a limited set of "primary" colorants real or imaginary, additive or subtractive and generates all color combinations from all possible mixture proportions of those primaries within a *mixture gamut*, or first defines fundamental perceptual dimensions of equal color difference, then locates colors within the *perceptual limits* of normal (average) color vision.

These models tend to have a characteristic form, as well. Colorant models are often represented in a *double conical* geometry, in which the hue circle is mixed with various proportions of white and/or black. In contrast perceptual models, as they enclose the irregular shape of perceptual color limits, choose instead a cylindrical form that does not impose any arbitrary geometry on the distribution of colors.

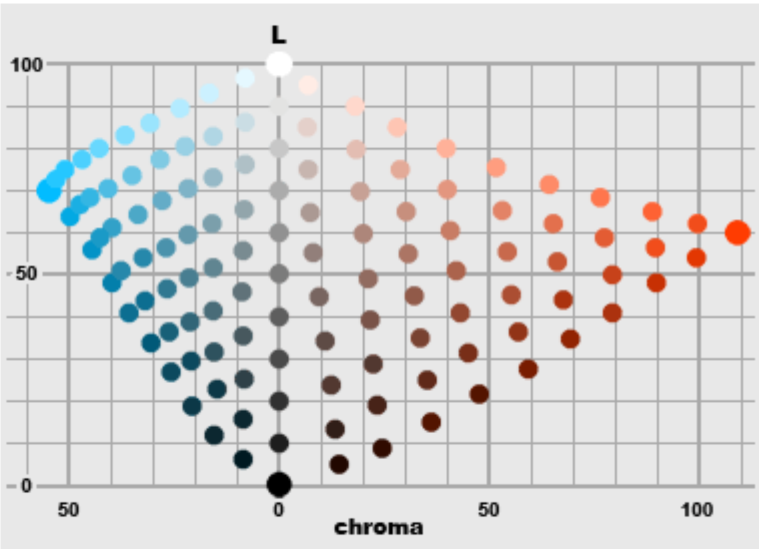


anatomy of a colorant model

The diagram (above) shows the logical structure of a pigment color solid of white (**W**), black (**K**) and "pure color" pigment (**C**). (Note that the "pure color" **C** must often be a mixture of two other pigments, which is necessary to produce the hue variety around the hue circle.)

The upper figure shows how the proportions of **W** and **K** are varied across a hue slice, each contributing from 0% to 100% of the total mixture and their combined percentages ranging from 0% at the side apex to 100% along the central axis or gray scale. The "pure color" is increased from 0% at the gray scale to 100% at the side apex of the hue slice. When the three pigments are combined according to these percentages, along with the complementary color opposite, the result is a diamond shaped slice through the color solid (lower figure). Equivalent slices are produced for incremental complementary hues all the way around the hue circle.

When a pigment color solid (indeed *any* media color solid, including the RGB color space of your computer monitor) is located within a uniform color space (such as CIELAB or CIECAM), the tidy triangular geometry appears significantly altered (diagram, below).



the colorant model in a uniform color space (CIELAB)

In this example, the perceived differences among the orange red mixtures are much greater than those among the green blue mixtures; the pure green blue, orange red and middle gray are all of a different value (lightness); and the contours of the K, W and C mixtures are curved rather than straight. These three differences are the inevitable result of producing a color solid through material pigment mixtures, and they are disguised by displaying the pigment mixtures within a rigid geometrical framework. The distortions result from differences in the lightness and chroma of the two pigments (or pigment mixtures) used to define complementary "pure" colors, and from differences in the relative tinting strength of the pigments in relation to black and white.

The variety of mixture models is enormous including the CIE Yxy (http://www.handprint.com/HP/WCL/color6.html#Ypsf) model based on imaginary (invisible) primary lights, the electronic RGB (http://en.wikipedia.org/wiki/RGB_color_model) standard based on real phosphors or lights, the Natural Color System (http://www.handprint.com/HP/WCL/color7.html#NCS) (NCS) based on imaginary (visualized) pure hues, or the various print regimes based on real CYMK (http://en.wikipedia.org/wiki/CMYK_color_model) inks. These models are generally developed for specific color reproduction applications (which use the specific primary colors in the model), are easy to implement, and have high practical utility.

The *uniform color space* (UCS) models, in contrast, , pigment models include the Runge (http://www.handprint.com/HP/WCL/color7.html#runge) and Chevreul (http://www.handprint.com/HP/WCL/book3.html#hemisphere) color solids and the Ostwald and Swedish NCS (http://www.handprint.com/HP/WCL/color7.html#NCS) color models. These are generally closer to the painter's traditional conceptions of color mixing; *saturation* is the preferred measure of hue purity, and hues are proportional mixtures of "pure colors" that are commonly either the painter's primaries (CYM) or artist's primaries (RYGB).

What is a color space good for? First, it provides an unambiguous way to systematically label and display colors using the colormaking attributes: any possible combination of lightness, hue and hue purity (chroma or saturation) locates a specific point in the color space, and that point represents every surface or object with those three color attributes. Second, a color space provides an explicit way to compare colors: similar colors will be located near each other in the color space, and very dissimilar colors will be located far apart, so we can use *distance* within the color space to specify the *perceived difference* between any two colors. Third, the color space allows the conceptual description or grouping of colors according to their *relative position* within the color space such as *complementary, triadic, analogous, nuance, shade, tone* or *tint*. Of course, this third purpose is how the hue circle, as a color wheel (http://www.handprint.com/HP/WCL/color13.html), has been used in traditional color theory.

misconceptions in traditional color theory

A large portion of the color theory taught to artists today is traditional color knowledge (http://www.handprint.com/HP/WCL/book3.html#edwards). Traditional means, established a long time ago in the 18th and 19th centuries, in fact. As with many ideas commonly believed in the 18th century (such as the inferiority of women, or the divine right of kings), most of these ideas are either patently false or useless as a guide to painting technique.

Before we can lay out a modern color theory, we have to address and dispell the most significant of these traditional color misconceptions. The most important, and the most enlightening to explore, involve "primary" colors and color mixtures.

12 misconceptions in traditional color theory

"Color" is either *in* light or *in* pigments.

All color is created by the mixture of three "primary" colors.

The three primary colors of paint are *red, yellow* and *blue*.

You cannot mix a primary *red, yellow* or *blue* using any other colors.

Saturated hue is the defining or "pure" color attribute.

The color of a paint is identical with the color of light it reflects.

Primary colors of paint cannot mix all possible colors, because paints are *impure* colors.

A "split primary" palette overcomes the *impurity* of paint colors.

With a split primary palette, do not mix colors "across the line" of a primary color.

Transparent watercolors achieve pure color because light is reflected from the paper through the pigments, "like light through a stained glass window".

Secondary colors are 1:1 mixtures of two primary colors, and *tertiary* colors are 1:1 mixtures of two secondary colors.

Painters use the primary color framework to analyze visual colors and paint mixtures.

I will address each misconception in turn, and either explain or demonstrate factually why it is wrong.

1. "Color" is either *in* light or *in* pigments.

We start with the traditional conception of what color *is*. To unravel this conception, ask yourself: *"what <u>kind</u> of color is a primary color?"* Is the color in a paint, or in the light, or in the mind? Can we have an ounce of yellow, or a lux of yellow, or a sensory unit of pure imagined yellow? Where is the yellow we are talking about?

Though references to three "primary" or "primitive" colors can be found as far back as the writings of the ancient Greeks and Romans, the primary color dogma as we have it today was first explicitly advanced in the early 1700's. The entrepreneurial German printer **Jakob Christoffel Le Blon** (1667-1741) stated the basic principles clearly in his *Coloritto: or the Harmony of Coloring in Painting Reduced to Mechanical Practice* (1725):

Painting can represent all visible *Objects with three Colours,* Yellow, Red *and* Blue; *for all other Colours can be compos'd of these* Three, *which I call* Primitive. ... *And a mixture of those* Three original Colours makes a Black, *and all* other *Colours whatsoever*. ... *I am only speaking of* Material *Colours, or those used by* Painters; *for a mixture of* all *the primitive* impalpable *Colours* [of light], *that cannot be felt, will not produce* Black, *but the very Contrary,* White, *as the great Sir Isaac Newton has demonstrated in his Opticks*. White, *is a Concentration, or an* Excess *of Lights*. Black *is a deep Hiding, or* Privation *of Lights*.

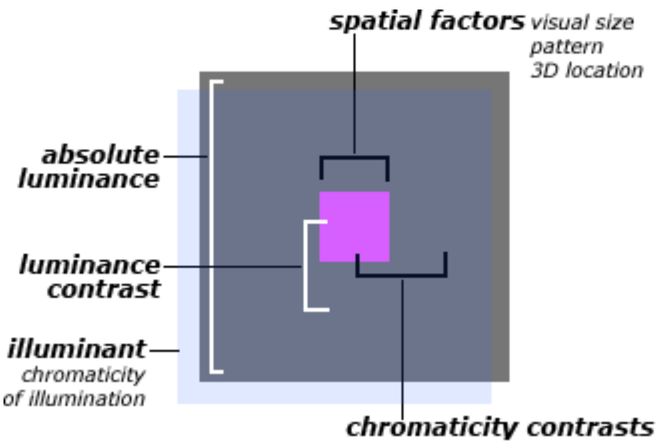
Although LeBlon emphasizes the distinction between colors of paint and colors of light, traditional color theorists quickly agreed that *all color is in the light,* as "colored light". They simply ignored the fact that Isaac Newton, in his *Opticks* (1704), carefully dismissed this idea (http://www.handprint.com/HP/WCL/color2.html#colormind), stating instead that **color is a sensation in the mind**: *"For the Rays [of light] to speak properly are not coloured. In them there is nothing else than a certain Power and Disposition to stir up a Sensation of this or that Colour."*

Well, *how* does light create the color sensation? The answer turns out to be both incredibly complex (http://www.handprint.com/LS/CVS/color.html) and still in part unknown. But artists can be guided by three basic concepts:

11. Color displays the relationship between light and light reflecting

surfaces in space.

12. The five components of visual color context are: (1) the total illuminance level, (2) the illuminant (chromaticity of the illuminance), (3) the illuminance contrast between color areas, (4) the colormaking contrasts between color areas, and (5) spatial factors (size of color area, pattern, location in space).



the five components of visual color context

The five components are:

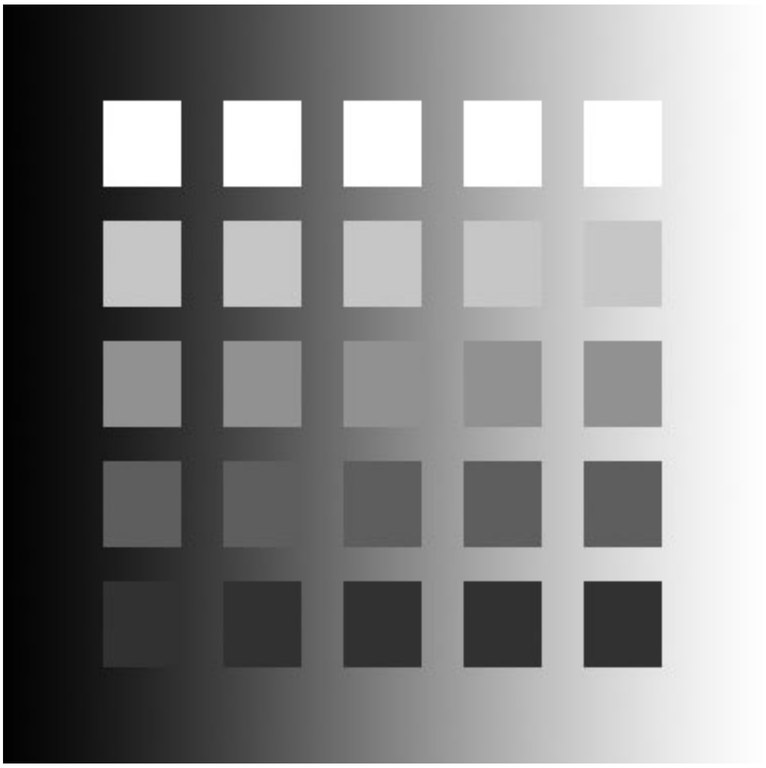
total illuminance level - this is the total quantity of light incident on (falling on) the colored surfaces or objects; a portion of this light is reflected by the surfaces to create their *luminance* or quantity of radiated light, which in turn affects the luminance adaptation (http://www.handprint.com/HP/WCL/color4.html#sensitivity) of the eye, the apparent brightness of the surfaces, and the range of lightness contrast.

illuminant - the combined hue and saturation (chromaticity) of all the light incident on the colored surfaces; this affects the chromatic adaptation (http://www.handprint.com/HP/WCL/color4.html#chromaadapt) of the eye, the color rendering (http://www.handprint.com/HP/WCL

/color12.html#colorrendering) properties of the light, and the range of apparent chromatic contrast.

illuminance contrasts - the quantity of light incident on the colored surfaces relative to the light incident on surrounding surfaces; a disparity between the two (http://www.handprint.com/HP/WCL/color4.html#lumcontrast) will increase or decrease the lightness and chromaticity contrast between the color area and the surround.

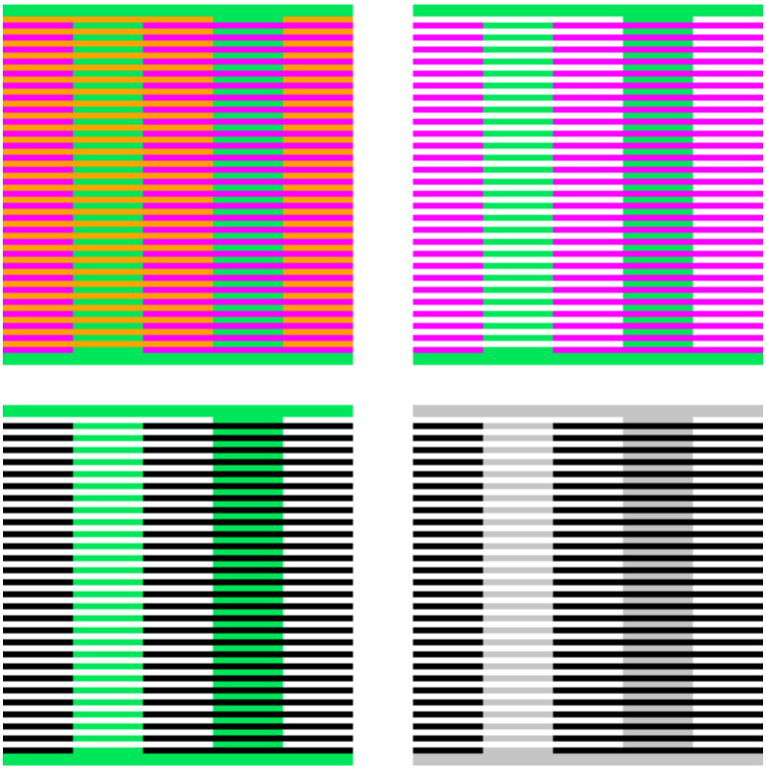
colormaking contrasts - the visual color difference in lightness, hue and hue purity between the color area and the surround when both are viewed under the same "white" illumination; this may cause a variety of localized chromatic induction (http://www.handprint.com/HP/WCL/color4.html#chromainduct) and chromatic adaptation effects.



color changes induced by simultaneous contrast on lightness

The example above illustrates the , or the change in lightness contrast induced by the lightness of the background. The gray panels in each row have exactly the same lightness, from light to dark, but the column on the far right appears to show the full range of lightness (from white to black) because it is on a light background; in the column on the far left the lightness contrasts appear condensed. This is why paintings and photographs are generally mounted on white, not black, mats.

spatial factors - the spatial interpretation (http://www.handprint.com /HP/WCL/color4a.html#spatialcolor) of the color area in relation to the total visual field; these include the visual size of the color area, its location within a surface pattern, and its location in three dimensional space relative to the viewer, to the light source, and to other surfaces or objects that may shadow or reflect light.

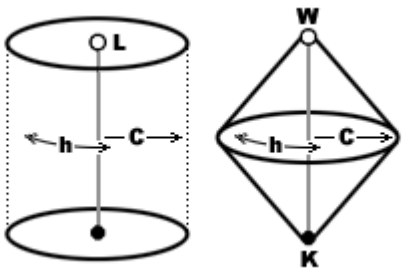


color changes induced by surface color patterns

The three examples (diagram above, top row and lower left) show the remarkable color changes that can occur in the same green color of "background" when overlaid by different colors of bands; the fourthe example (lower right) shows that these effects extend to achromatic contrasts as well. These complex and visually powerful pattern effects, as they appear in textile patterns, were the original impetus for the famous 19th century color studies by Michel-Eugène Chevreul (http://www.handprint.com/HP/WCL/book3.html#chevreul).

Our natural way to talk about color is that it is *in* something in light or in paints. In fact, it is in *both* lights and materials, and in their spatial relationships as well.

What is color *for?* to reveal the world.



characteristic geometry of
color spaces

colorant spaces typically have a double cone structure (left); perceptual spaces have a cylindrical structure (right)

13. Color vision compensates for illuminance variation, minimizes illuminant color and enhances colormaking contrasts as necessary to make light and color consistent with spatial factors (objects in space).

There are many striking and delightful illustrations of the effect that spatial factors can exert on color appearance, and these are . For now, the example of an illuminated cube (image, right) will demonstrate the basic effect.

Vision interprets this image as a cube under illumination that falls unequally on the three visible sides; and it construes the three sides as showing an identical tiled pattern consisting of 1 very dark central tile, surrounded by 4 dark tiles, surrounded by 8 light tiles, in a field of 12 white tiles. Color vision adopts the perception of a uniform pattern on each face of the cube to compensate for the variations in illumination, so that the pattern on each face seems to consist of the "same" four colors.

However, if we eliminate the illumination cues from extraneous tiles, we discover that the *very dark* tile in the top pattern is actually the same digital color as the 4 *dark* tiles on the left side and the 12 *white* tiles on the right side! In other words, color vision has taken perceptually dark color areas and subjectively lightened them so that the are consistent both with an identical surface pattern on each face of the cube and with differences in illumination across different faces of the cube.

14. Surfaces in space define areas of reduced color contrast separated by edges and colors of enhanced color contrast.

Color adheres to our world, it appears firmly woven into materials and light. It is an essential dimension of our experience of space. All of this is the result of complex processes of adaptation, anchoring and contrast (http://www.handprint.com/HP/WCL/color4.html).

Despite the complexity, much of color perception is *implicit*. We are rarely conscious of the judgmental process that goes into defining color in a specific situation, under a specific kind of light in a specific spatial location. We simply *see* the color *as* illuminated objects in space.

The color of surfaces and objects is fundamentally sensitive to the light illuminating them the intensity of the light, and its color.

Color changes radically as the intensity of illuminance changes from faint (such as moonlight) to bright (such as noon daylight). As light increases, colors become more saturated, hues expand into subtle shades, and the contrast between lights and darks increases. In darkness, all colors are reduced to gradations of gray.

The color of the light mixes subtractively with surface colors. Under yellow light, green blues appear green, reds appear orange, grays appear yellow, and blues appear gray.

The eye preserves these color changes but the mind disregards them.

Color vision is designed to create a clear image of the physical world. To do this, it contains numerous processes that adjust color appearance to match a sensible idea of what we are looking at.

As objects recede in the distance their color variations average out and their edges become more indistinct. As objects approach, their surface color variations increase and their edges become more distinct.

2. All color is created by the mixture of three "primary" colors.

An artist aware of the first three color principles immediately understands how "color is created by primary colors" is an inadequate description of color experience.

But, even if we limit the discussion to how colors can be mixed, or duplicated, or perceived by the eye, the belief that "primary" colors can create all colors is false.

15. All "primary" colors are either imaginary concept colors or imperfect material colors. No visual color is "primary".

If we chase primary colors down to their fundamental nature, we find there are actually *two kinds* of primary colors: the "primary" colors we use to **explain color**

mixtures (for example, "red, green and blue primaries mix all colors of light"), and the primary colors we use to actually **make color mixtures** ("to match that orange color, mix three parts yellow and one part red paint").

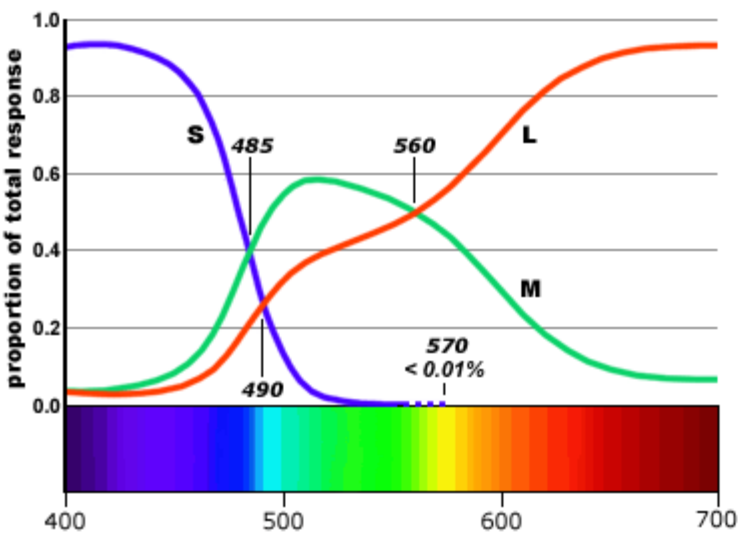
And if we examine the behavior of these two different kinds of primary colors, we discover a remarkable **primary color paradox**:

The three primary colors we use to EXPLAIN COLOR MIXTURES are all imaginary: they are invisible to our eyes and have no physical reality.

The three primary colors we use to MAKE COLOR MIXTURES are all imperfect: they cannot mix all colors.

The detailed explanation of this paradox is provided on another page (http://www.handprint.com/HP/WCL/color6.html#imaginary), but both these facts arise from the design of the eye: specifically, the way our **L**, **M** and **S** cone sensitivity curves (http://www.handprint.com/HP/WCL/color1.html#normconesens) overlap in responding to light wavelengths.

This is easiest to see if we look at the proportion of the eye's total color response that comes from each of the three types of cones, for each single wavelength (hue) across the visible spectrum (diagram, below).

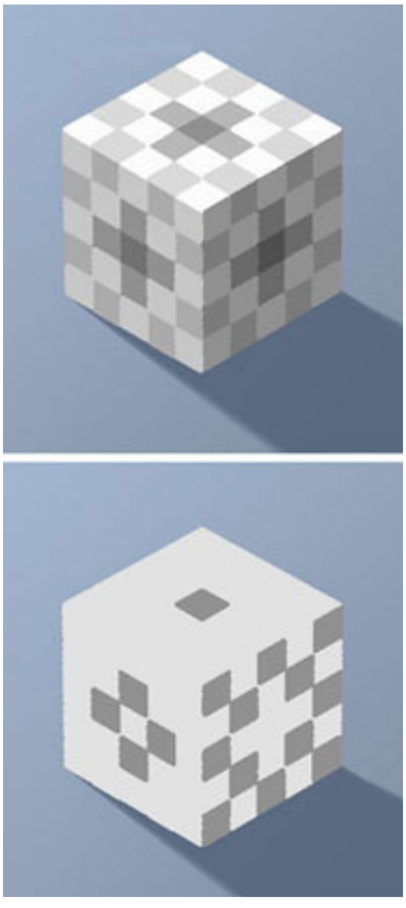


wavelength (nanometers)

L, M and S cone responses to light

proportion of total color signal from each type of cone produced by a single spectral wavelength, across the visible spectrum; every wavelength stimulates at least two types of cone

Single wavelengths of light create the most saturated color sensations possible. Yet, as the diagram shows, any single wavelength of light will stimulate at least two and (at wavelengths less than ~570 nm) all three cones at the same time. There is no wavelength that stimulates one cone 100% and the other two cones 0%. So we never see a "pure" response from any single cone, and we never see "pure primaries" in our visual experience. We always see only *visual color mixtures*.



spatial interpretation strongly affects color appearance

a cube tiled in four colors (top); tiles that are the same digital color (bottom)

When we map these proportional **L**, **M** and **S** cone outputs in what is called a trilinear mixing triangle (http://www.handprint.com/HP/WCL/color1.html#triprinciples), we discover that these overlapping cone responses to single wavelength light create a curved limit on the maximum chroma possible across hues from yellow green to blue. This curved boundary encloses the area of all possible hue and chroma combinations, called a **chromaticity diagram** (diagram, right).

This curved boundary **makes a visible primary color that can mix all other colors impossible**. Here's why:

If we choose three *real* primary colors of light (**R**, **G** and **B**, diagram right), the mixtures possible with those three "primaries" create a mixing triangle (an **RGB** gamut) that does not contain the entire chromaticity space the *real* primaries cannot mix all colors.

If we define three *mathematical* primary colors (**X**, **Y** and **Z**, diagram right), whose **XYZ** gamut contains the entire chromaticity diagram and therefore explains all possible colors, then these imaginary "primaries" must be located *outside* the chromaticity diagram, and are therefore invisible. And how can a color be a *color,* if you can't *see* it?

Because it is impossible to create a primary color that is both a real (visible) color and that can mix all other colors, **all color theory primary colors are either conceptual or material: either imaginary or imperfect**.

Again, when it is important to keep this distinction in mind, *conceptual color* identifies an abstract or ideal color instead of a real or physically possible color, and *material color* identifies a physical colorant or light that can or does create a color perception in actual experience.

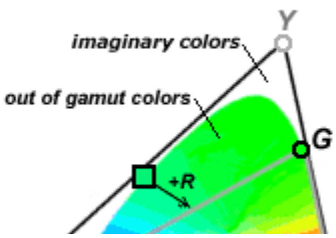
3. The three primary colors of paint are *red*, *yellow* and *blue*.

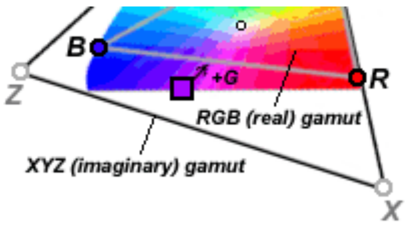
The first misconception to set aside is the old "red, yellow and blue" nursery rhyme. As I , the subtractive (paint mixing) primaries can be precisely defined:

16. The ideal subtractive primary hues are red violet [magenta], yellow and green blue [cyan].

Red and blue cannot be primary colors because they lack the "blue" or short wavelength reflectance (for red) or "red" or long wavelength reflectance (for blue) that must be present in both colors to allow red and blue to mix a violet color. Blue also lacks the "green" or mid wavelength reflectance necessary to mix a saturated green with yellow. As Moses Harris (http://www.handprint.com /HP/WCL/color14.html#harris) pointed out 260 years ago, *"red and blue will not make a fine purple, which every painter knows"*.

It will be helpful to understand the double life of primary colors, as conceptual colors and material colors, over the past three centuries. On the one hand, "primary" pigments, inks or dyes must be available to be used, and the availability of colorants has depended on pigment manufacturing technology. On the other hand, the choice of primary colors has always focused on practical considerations colorant cost, physical attributes, and the color mixtures that result.





all primary colors are either imaginary or imperfect

spectral primaries RGB, which are visible, can't mix all colors; mathematical primaries XYZ, which explain all color mixtures, are invisible

Available Colorants. There have been truly amazing advances in pigment chemistry over the past 300 years. (For a history, see *Bright Earth: The Art and Invention of Color* by Philip Ball (http://www.handprint.com/HP/WCL/book2.html).) Adapting to these changes in art materials, traditional color theory has fixed on very different choices of "red", "yellow" or "blue" primary paints.

In the earliest subtractive color printing system, devised by Le Blon (http://www.handprint.com/HP/WCL/color6.html#leblon) in the early 1700's, the primary colors were a mixture of carmine, madder lake and vermilion (mixed to make red), yellow lake, and iron blue (PB27 (http://www.handprint.com/HP/WCL/waterb.html#PB27)) the best pigments for the job available in the early 18th century. The artists' color wheel proposed by in 1772 used vermilion, orpiment and natural ultramarine blue; Johann Lambert (http://www.handprint.com/HP/WCL/color6.html#lambert) in 1785 preferred gamboge, carmine and iron blue. Charles Winter's 20th century used alizarin crimson, cadmium lemon and phthalo blue. Contemporary painters and printers would probably prefer a benzimidazolone yellow, quinacridone magenta, and phthalo cyan.

As a reference, the diagram (right) shows the location of the magenta, yellow and cyan, defined as optimal colors (the most saturated surface colors possible) located on the CIELAB (http://www.handprint.com/HP/WCL/color7.html#CIELAB) **a*b*** plane.

Painters and color theorists since the 18th century have chosen their primary triad palette (http://www.handprint.com/HP/WCL/palette4c.html) from among the labeled pigments. Thus, the "true" primary red was originally either vermilion (PR106 (http://www.handprint.com/HP/WCL/waterr.html#PR106)) or a lake of cochineal or madder (NR4 (http://www.handprint.com/HP/WCL/waterc.html#NR4)). Late in the 19th century the primary red became alizarin crimson (PR83 (http://www.handprint.com/HP/WCL/waterr.html#PR83)), and today the most popular recommendation is a violet red quinacridone (PR122 (http://www.handprint.com/HP/WCL/waterc.html#PR122) or PV19 (http://www.handprint.com/HP/WCL/waterc.html#PV19R)). Notice that all these primary colors are very far from the ideal magenta hue.

The ultramarine blue primary chosen by Harris is actually closer to the ideal magenta than to the ideal cyan, and since his time the pigments used for primary blue have evolved only about half way toward the ideal cyan hue. And while the primary yellow pigments have always been closest to the ideal, they are still shifted toward the red primary by a significant amount.

Practical Considerations. Pigment availability is not the only reason for these shifts away from the ideal subtractive primary colors. The "ideal" pigments cobalt violet (PV49 (http://www.handprint.com/HP/WCL/waterv.html#PV49)), cobalt teal blue (PG50 (http://www.handprint.com/HP/WCL/waterg.html#PG50)) and bismuth yellow (PY184 (http://www.handprint.com/HP/WCL/watery.html#PY184)), underlined, are commonly available today: why don't artists and printers use them?

One issue is cost. Cobalt violet, which appears to be the "ideal" subtractive primary magenta, is one of the most expensive pigments available even when compared to micronized quinacridone pigments.

A more important issue is handling attributes. Cobalt violet has a weak tinting strength, and it only appears to have a strong saturation when the particle sizes are relatively large (when ground into fine particles, the color becomes weak and whitened). To get a strong color, a dense, thick application of coarse pigment would be required, and this would appear unpleasantly crusty on a printed page. Cobalt teal blue and bismuth yellow have a similar gritty, grainy texture, so all three would clog up a printing press and intrude in a printed texture. They are also opaque, which would make overprinted colors hard to control and turn their subtractive mixtures muddy.

A third issue is . While painters and printers historically have been nonchalant on this issue, by the 20th century they had learned to avoid the most fugitive dyes available, and have generally migrated toward more lightfast pigments as soon as they became available. Thus, 18th century carmine lakes provide very handsome violet reds, but those colors faded relatively quickly, and by the 19th century substitute pigments were being used instead.

But the most important issue is the color mixtures that pigment choices can produce. Even if a physically ideal (transparent, finely divided, intensely saturated, light valued) red violet pigment were available, the orange mixtures it would make with yellow would be relatively dull, compared to oranges mixed with a violet red. For these reasons, painters happily use a hue of "primary" yellow that is theoretically too red, and a "primary" magenta that is theoretically too yellow, because the resulting range of color mixtures is, on the whole, the most satisfying to the eye. Printers and painters focus on the entire range of color mixtures that a subtractive palette can actually create, not on the theoretical or ideal color of the paints or inks by themselves.

What makes these tradeoffs feasible and often unnoticeable in practice is the remarkable ability of our color vision to **accept different color images as equivalent or identical**, provided the used to reproduce the images retain the *relative relationships* between all the colors in the image, especially the relative differences in lightness and hue.

And pigment innovation is still creating new primary palettes and new systems of color mixing. Thus, violet red (http://www.handprint.com/HP/WCL/palette1.html#violetred) (magenta) was not standardized as a subtractive primary color until the CMYK printing system was invented by Alexander Murray in 1934. The CMYK system, in turn, cannot reproduce many saturated oranges, violets, blues and yellow greens, and in specific applications where brighter colors are required, newer printing systems with larger gamuts Hexachrome (six primary colors of ink) or Heptatone (seven primary colors) can be used instead.

17. The choice of primary colors is arbitrary; colorant selections depend on cost, availability, convenience, medium and image quality.

It is remarkable how hidebound traditional color theorists have become. A case in point: Betty Edwards (http://www.handprint.com/HP/WCL/book3.html#edwards) recommends the use of the 19th century pigment alizarin crimson (PR83 (http://www.handprint.com/HP/WCL/waterr.html#PR83)) because, she claims, there is no better red violet pigment available. This is factually false: there are several quinacridone pigments, including quinacridone rose (PV19 (http://www.handprint.com/HP/WCL/waterc.html#PV19R)) and quinacridone magenta (PR122 (http://www.handprint.com/HP/WCL/waterc.html#PR122)), that produce far more saturated and variegated mixtures than alizarin crimson and are far more lightfast.

As another example, some traditional color theory texts assert that there is one set of primary colors used in printing and a different set used in painting. This is a remarkable misconception, because modern paints and printing inks are manufactured using *exactly the same chemical pigments*. The real constraint here is that modern printers have adapted to use pigments that mix the widest range of colors, while painters cling to the primary pigments that were used a century ago.

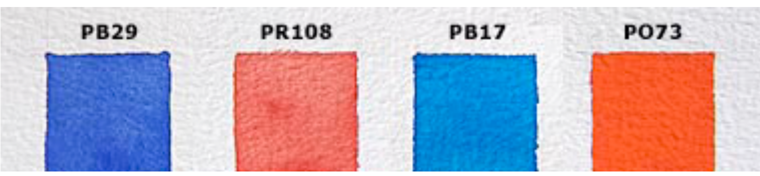
18. The subtractive primary hues are the same in all printing, painting and photographic media. The optimal subtractive primary pigments are identical in painting and in printing.

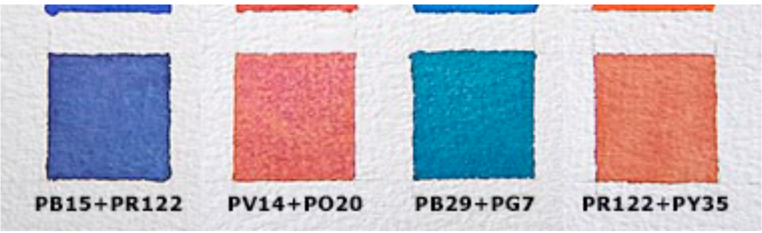
The missing qualification is, of course, ... *for painters that actually use a primary color palette*. I know of no living painter who does so exclusively. Even in the 18th century, painters used as many different pigments as they could afford to lay their hands on, and that is still true today. In modern color theory there are only , and these can be literally any number and color of paints an artists prefers.

4. You can't mix a primary *red, yellow* or *blue* using any other colors.

The keystone belief in traditional color theory has always been that it is not possible to mix a "primary" color using other colors. This has been for three centuries the ultimate guarantee that primary colors really are "primary".

As you might guess by now, this claim too is false. Every painter knows that it is possible to mix a very fine turquoise from ultramarine blue (PB29 (http://www.handprint.com/HP/WCL/waterb.html#PB29)) and phthalocyanine green (PG7 (http://www.handprint.com/HP/WCL/waterg.html#PG7)), or a decent red from cobalt violet (PV14 (http://www.handprint.com/HP/WCL/waterv.html#PV14)) and cadmium orange (PO20 (http://www.handprint.com/HP/WCL/watero.html#PO20)) (image, below).





traditional color theory has decreed it

matching violet blue ultramarine (PB29) or red orange pyrrole (PO73) is "possible"; matching cadmium red deep (PR108) or phthalo green blue (PB17) is "impossible"

Certainly these mixtures are somewhat dull, but not any duller than the orange one gets by mixing "primary" quinacridone magenta (PR122 (http://www.handprint.com/HP/WCL/waterc.html#PR122)) and "primary" cadmium yellow (PY35 (http://www.handprint.com/HP/WCL/watery.html#PY35)), or the violet blue one gets by mixing "primary" quinacridone magenta with "primary" phthalocyanine blue (PB15 (http://www.handprint.com/HP/WCL/waterb.html#PB15)). When we compare these mixtures to single pigment violet blue, green blue (PB17 (http://www.handprint.com/HP/WCL/waterb.html#PB17)), red (PR108 (http://www.handprint.com/HP/WCL/waterr.html#PR108)) or orange paints (PO73 (http://www.handprint.com/HP/WCL/watero.html#PO73)), the "possible" and "impossible" mixtures look pretty much the same.

If we believe traditional color theory, then certain dull or dark mixtures are just fine, whereas other dull or dark mixtures are "impossible". We confront the special pleading, or outright misconception, that is necessary to keep the shaky "primary" color dogma on its feet. Modern color theory simply sticks to the facts:

19. Every hue can be mixed by two other hues, provided the two hues are not directly opposite each other on the hue circle, and the hue to be mixed

is located within the shorter distance between them.

Yellow is a special case, because a mixed yellow will appear dark and greenish, as a raw umber or green gold. However this is because our visual system distinguishes between a saturated and unsaturated yellow with a visual contrast that does not appear in magenta or cyan hues, as .

5. Saturated hue is the defining or "pure" color attribute.

The rigamarole about what can or cannot be mixed with primary colors reveals a subtle but important prejudice in traditional color theory: that "color" is synonymous with *saturated hue*.

This is most apparent in the abbreviated way that colors are specified in traditional color theory discussions of color design. When the color crank Johannes Itten announces that *"yellow against purple provides a very large contrast between light and dark"* he visualizes a saturated (light valued) yellow and a saturated (dark valued) purple. Dark valued yellows are blackish, and light valued purples are whitish, but he ignores those variations.

As we've seen, color is defined by at least (lightness, hue and chroma/saturation), but color theory generally uses hue labels alone *primary yellow, pure yellow* to denote colors. This code works as follows: designate a hue, then find the in that hue, and that is the hue, lightness and chroma that is intended. "Yellow" means a light valued, high chroma yellow hue.

This seems sensible, because it is how we naturally talk about color. If someone says "she was wearing a red dress", you do not imagine the dress as maroon or pink, which are also red hues. But the code is unproductive when only saturated hues are used to generalize about color design, for example as a contrast between *yellow* and *violet*. In modern color theory, any meaningful statement about color relationships has to specify all three color attributes.

20. All three colormaking attributes lightness, chroma and hue are equally important to evaluate visual colors and create color designs.

Much of the traditional color theory design recommendations depend on the preference for saturated color and a or dull color, but these prejudices get in the way of choosing the best color design for a specific application.

21. The relative importance and optimal values of color lightness, chroma and hue in a color design depend entirely on visual style, the materials used, the purpose of color choices and the context in which color will be viewed.

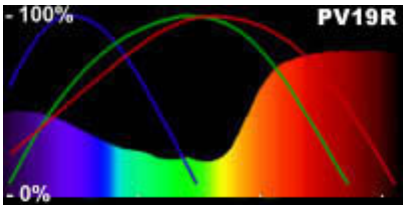
Traditional color theorists are fond of using the term "spectrum" to denote a color, as in "spectrum yellow" or "spectrum red". This means, apparently, either a "pure" yellow or red, or a yellow or red of a specific hue. The usage is silly, as *all hues* of yellow are present and equally at maximum saturation or hue purity in the light spectrum, and because a "pure" red is actually not visible in the spectrum at all it is an extraspectral mixture of "red" light tinted with "violet" light. But spectral hues are the most saturated color stimuli possible, and (for traditional color theorists) *saturated color* is the defining color attribute.

6. The color of a paint is identical with the color of light it reflects.

Mention of the term "spectrum" takes us in a different direction and introduces the story of color itself. Why do paints have the colors they do? The traditional color theory answer is that the color of the paint is identical with the color of light it refects. Here Isaac Newton is the 18th century authority:

All colour'd Powders do suppress and stop [absorb] *in them a very considerable Part of* *the Light by which they are illuminated. For they become colour'd by reflecting the Light of their own Colours more copiously, and that of all other colors more sparingly."* (*Opticks,* Book I, Part II, Experiment 15)

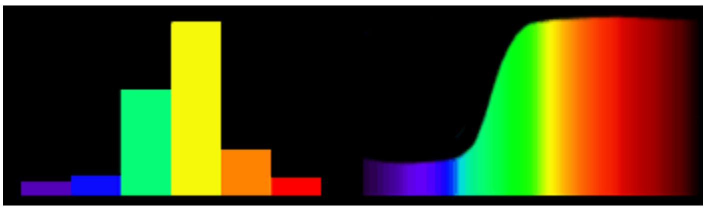
This is true in a figurative sense: materials differ in the light they reflect, and these differences are the material *cause* of the visual color. For that reason radiant color is described with a *spectral reflectance profile* or **reflectance curve**, which shows the proportion (between 0% to 100%) of "white" light that is reflected by the material at each visible wavelength.



reflectance curve of a violet red paint

The error is that different sections of the spectrum appear to have different visual color, but these are *not the same* as the visual color of the same light as reflected from material surfaces. The difference arises in the complex processes by which our eyes and mind *interpret* light as visual color. This interpretation frequently causes the color of materials to differ from the color of the light they reflect.

For example: Michael Wilcox (http://www.handprint.com/HP/WCL/book3.html#wilcox) adopts the 19th century explanation of color mixure in terms of six complementary hues, but to make this explanation plausible he must describe yellow paint as a material that reflects primarily "yellow" light (diagram, below).

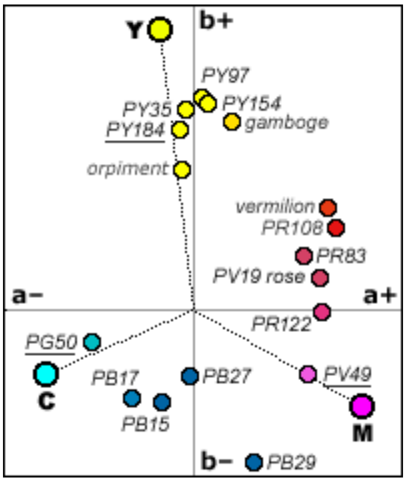


"colored light" reflected from a greenish yellow paint

the Michael Wilcox story using six basic hues (left), and the way it really is (right)

Why would Wilcox describe the light mixture reflected from yellow paint ("red" and "green") as if it were a paint mixture (yellow mixed with some green)? Because he is quoting a traditional color theory paint mixing calculus (http://www.handprint.com/HP/WCL/color14.html#chevreul). To operate this calculus, the artist "deconstructs" the *visual color* of the paint into six traditional complementary colors (http://www.handprint.com/HP/WCL/color13.html#secondary) (the six colored bars in the diagram). These hues are mutually exclusive: yellow cancels violet, orange cancels blue, red cancels green, in each case resulting in a gray mixture. The calculation is done from the verbal labels: if the artist mixes an *orange yellow* with a *green blue*, he can assume that the orange cancels the blue to produce gray, and this gray will dull the mixture of green and yellow that remains.

However, "yellow light plus some green light" is not what appears in the reflectance curve of a saturated yellow paint (diagram, above), which reflects nearly all the incident "red", "orange", "yellow" and "green" light. This is necessary for the yellow to create attractive .

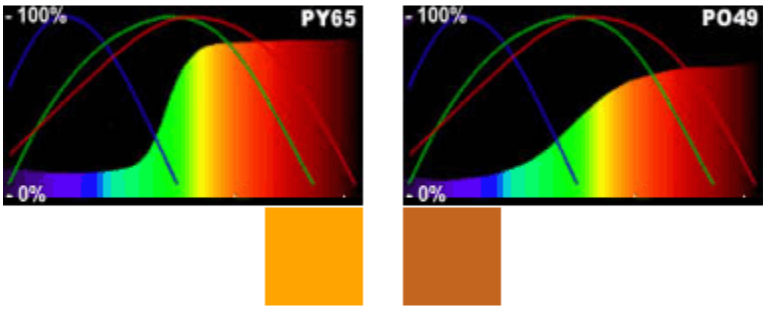


subtractive primaries as optimal colors and as available pigments

as located on the CIELAB a*b* plane

If we take traditional color theory at its word, then some ideal material that reflects *only visual yellow light* should appear to be a remarkably pure yellow. Although such a material apparently does not exist, it is possible with the tools of colorimetry (http://www.handprint.com/HP/WCL/color6.html#colorimetry) to specify what such a "perfect yellow" material would look like. And this color theory yellow turns out to be a dark umber or dark green gold (diagram, right)!

The problem here is that the eye places a special requirement on yellow hues: they must not only reflect red, orange and yellow light, they must reflect *nearly all* the red, orange and yellow light that falls on them. Materials that reflect only some of the light fall in the unsaturated color zones (http://www.handprint.com /HP/WCL/color12.html#unzones) and appear instead to be umber or green gold. The problem is not in the *color* of the reflected light, since this is almost identical between a saturated and dull *orange yellow:*



reflectance curves of two orange yellow paints

(left) cadmium yellow deep, PY65; (right) quinacridone gold, PO49, with visual color samples matched in Lab color space

Instead, the most important factor is the between the color and surrounding surfaces. The quinacridone gold reflects marginally less light than the cadmium yellow deep, and therefore appears darker. This is enough to make the color appear quite different, as shown by the visual color samples.

22. The color of a paint is not in the reflected light, but in the visual interpretation of the reflected light.

The yellow example highlights the three major reasons visual color differs from radiant color:

the light is interpreted by the eye as an , which has its own peculiar rules: among them, that "red" light and "green" light make yellow, or that "red" light and "violet" light make magenta.

the additive mixture in surface colors is interpreted not as a quantity of light, but as a *proportion of incident light:* in some cases, as in difference between yellow and ochre, a material reflects *most* of the incident light and still appear to be a different color than a material that reflects *almost all* the light.

the proportion of incident light is interpreted as a *contrast within the light environment:* regardless of the proportion of light it reflects, the same surface can appear depending on the contrast between its luminance (total reflected light) and the average luminance of the surfaces around it.

These issues get us ahead of the story and into the problems of . For now, let's pursue the causes of color as these are explained in traditional color theory.

7. Primary colors of paint cannot mix all possible colors, because paints are *impure* colors.

The previous error exposes the fundamental strategy in traditional color theory:

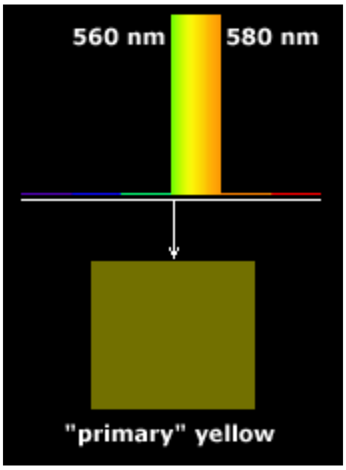
to rationalize rather than explain color mixtures. This appears clearly in the next error: that "primary" paints cannot mix colors as they ought to because paint colors are *impure* or *imperfect*.

This assertion also goes back to the misconceptions of the 18th century. It is alluded to in the color wheel text by Moses Harris (http://www.handprint.com/HP/WCL/color6.html#harris), and it is repeated without challenge in Michel-Eugène Chevreul's Principles of Color Harmony and Contrast (http://www.handprint.com/HP/WCL/book3.html#chevreul) (1839):

We know of no substance [pigment or dye] *that represents a primary color that is, that reflects only one kind of colored light, whether pure red, blue or yellow. ... As pure colored materials do not exist, how can one say that violet, green and orange are composed of two simple colors mixed in equal proportions? ... Instead we discover that most of the red, blue or yellow colored substances we know of, when mixed with each other, produce violets, greens and oranges of an inferior intensity and clarity to those pure violet, green or orange colored materials found in nature. They* [the authors of color mixing systems] *could explain this if they admitted that the colored materials mixed together reflect at least two kinds of colored light* [that is, two of the three primary colors], *and if they agreed with painters and dyers that a mixture of materials which separately reflect red, yellow and blue will produce some quantity of black, which dulls the intensity of the mixture*. [1839, ¶¶157-158; my translation]

There are three answers to the traditional color theory accusation that material or radiant colors are "impure" or "imperfect". The first answer is: yes, *all primary colors are either imaginary or imperfect* as . However the fault here is not in any way connected to the materials, or to the fact that they reflect "different kinds of light", but in the overlap among the **L**, **M** and **S** cone sensitivity curves.

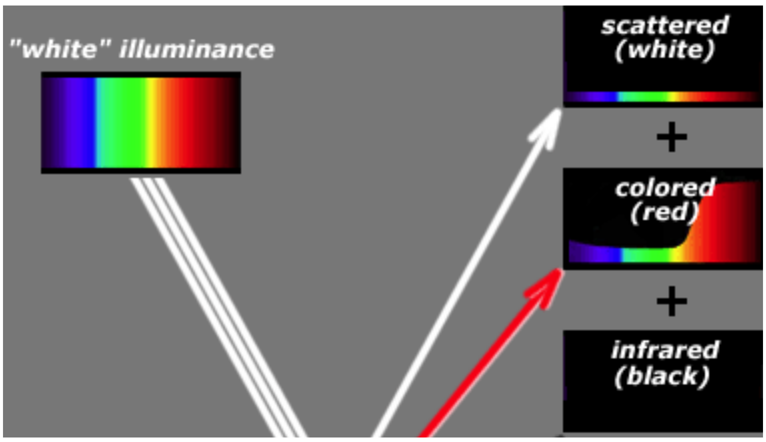
The second answer is that *radiant colors must be "impure", to make attractive color mixtures*. The of two paints only reflects the light that *both* paints reflect separately. This is because subtractive mixture of the materials that are mixed: any reflectance that is lacking in one of the paints will also be substantially lacking in the mixture. As a result, *yellow* and *blue* must both be high in "green" reflectance to make a saturated *green* mixture; *yellow* and *magenta* must both be high in "orange" and "red" reflectance to make a saturated *orange* mixture. So **subtractive mixture requires the primary colors to be "impure"** in order for them to be "primary". Each primary must reflect light from .

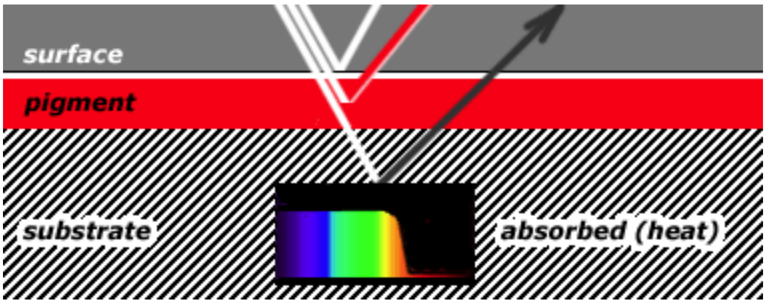


color theory yellow

the color appearance of a "pure" yellow paint that reflects 100% of "yellow" light

There is, however, a pervasive kind of "impurity" that does reduce the lightness and saturation of all material colors. But it is not a kind of impurity that is described in traditional color theory.





the three components of material color

The diagram (above) shows how three components of color arise in the three separate outcomes that occur when a light photon strikes a material surface:

scattering: when light strikes any surface, some amount of it does not affect a change in the electron distribution within the molecules that compose the material. The light is simply reflected back into the environment, 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.

chromatic reflectance: a substantial portion of the light does throw its energy into the molecules that compose the material, which disrupts the electron energies within the molecules that compose the material. This light promptly emitted at specific wavelengths that aggregate into the *chromatic reflectance* of the material. Some materials produce better chromatic reflectance than others, but many synthetic red, orange and yellow pigments produce chromatic reflectance with a hue purity that is very close to the physically possible maximum (http://www.handprint.com/HP/WCL/color3.html#huepurity).

infrared reflectance: the remainder of the light is transformed by interaction with the material molecules into heat. Some of this heat is held in the material, the rest is emitted back into the environment. However heat is invisible to the human eye light goes in, nothing visible comes out so the reflected heat adds a component of *blackness* to the visual color.

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

23. All visual colors originating in materials comprise a proportion of chromatic reflectance (C), a proportion of whiteness (W) caused by surface scattering, and a proportion of blackness (K) caused by the loss of light as heat:

visual color = W + C + K

Nearly all , such as Wilhem Ostwald's *Farbkörper* (1919) or the Swedish Natural Color System (http://www.handprint.com/HP/WCL/color7.html#NCS) (1981) require the sum of **W** (including white scattering and whiteness increased with a white pigment), **C** and **K** (including blackness increased by a black pigment) to equal a constant (1 or 100) for all colors.

Finally, with reference to the material surface attributes:

24. The proportion of white light scattering is decreased by surface gloss; the proportion of black absorptance is increased by a transparent vehicle.

Materials generally present both darker and more saturated visual color when they are enclosed in a transparent medium (such as acrylic or water) than when they are viewed as dry powders or embedded in an opaque vehicle. The transparent medium tends to trap the light and permit it to interact with more of the colorant molecules, increasing the probability that it will be transformed into heat or chromatic reflectance; it also presents a smoother surface, which greatly reduces surface scattering.

Although **W**, **C** and **K** are aspects of material color, they only become recognizable as attributes of visual color through properties of reflected light within the light environment, specifically through the interaction of and *chromaticity contrast*.

25. The visual color attributes W, C and K are perceived through luminance and chromaticity contrasts within a light environment, and therefore can be mimicked by contrasts between light stimuli presented as contiguous color areas.

This is how we can perceive blackened or whitened surfaces in an image presented on a computer monitor, television screen or projected transparency. The overall luminance of the image is interpreted as the light environment in much the same way as it would be in a physical environment, and the luminance and chromaticity contrasts are interpreted in the same way as they would be in surfaces.

However, the fact that we can simulate surface color attributes in the pure spectrum colors held in such high esteem by traditional color theorists only demonstrates that the imperfections we can simulate are also inherent in our visual response to the world, and therefore once again! are due to our eyes and mind, which anticipate the three part "impurity" of material colors.

8. A "split primary" palette overcomes the *impurity* of paint colors.

We've seen that the "impurity" of material color is inherent in material colorants, is essential for subtractive mixture to work properly, and is even essential to the visual color of a saturated yellow. Nevertheless, traditional color theory has attempted to fix this impurity. Let's see how.

The passage from Chevreul's The Principles of Color Harmony and Contrast (http://www.handprint.com/HP/WCL/book3.html#chevreul), quoted above, continues this way:

It is also certain that the violets, greens and oranges resulting from a mixture of colored materials are much more intense when the colors of these materials are more similar in hue. For example: when we mix blue and red to form violet, the result will be better if we take a red <u>tinted with blue</u>, and a blue <u>tinted with red</u>, rather than a red or blue leaning toward yellow; in the same way, a blue tinted with green, mixed with a yellow tinted with blue, will yield a purer green than if red were part of either color. (1839, ¶¶157-158; my translation; emphasis in original)

According the Chevreul, a yellow primary paint must reflect "yellow" light mixed with some "blue" or "red" light, which dulls the pure yellow color. As we can't avoid this color pollution, we minimize it by mixing colors tinted with each other so the thinking goes.

This is the basis for the traditional color theory remedy for dull paint mixtures the split "primary" palette (http://www.handprint.com/HP/WCL/palette4r.html). It is based on Chevreul's concept of "taint". The strategy is to *increase the taint* by splitting the paint primary colors into a "warm" and "cool" pair that are "tainted" or lean toward each of the other two primaries.

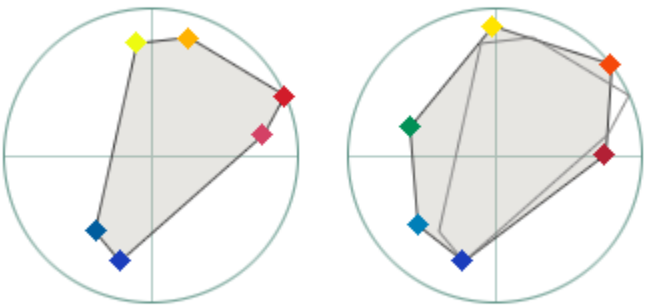
Thus we split primary yellow into a "warm" *orange yellow* (tainted with some of primary red) and a "cool" *green yellow* (tainted with some of the primary blue); we split primary red into a "warm" *orange red* (tainted with some of primary yellow) and a "cool" *violet red* (tainted with some of the primary blue); and we split primary blue into a "warm" *violet blue* (tainted with some of primary red) and a "cool" *green blue* (tainted with some of the primary yellow). The primary palette of three paints becomes a split primary palette of *six* paints.

Then, by mixing the primary paints that lean toward each other, taint mixing with taint is the same as color mixed with color. In theory, then, this solves the problem of dull orange, green and purple mixtures in a primary triad palette.

So let's hold the split primary palette to its key claim: that splitting the paint primary colors into a "warm" and "cool" pair allows us to mix the most vibrant secondary colors (orange, purple and green).

We evaluate the "vibrant color" justification for the split primary palette by comparing it to any other palette of six paints, for example the secondary palette (http://www.handprint.com/HP/WCL/palette4e.html), to see which paint selection is superior. There are two ways to do this.

A simple "back of the envelope" approach is to print out a copy of the pigment map presented on the CIECAM $a_C b_C$ plane (http://www.handprint.com /HP/WCL/camwheel.html), identify on this map the location of the pigments used in all paints in the palette (use the complete palette (http://www.handprint.com/HP/WCL/palette1.html) to identify pigments from the color index name (http://www.handprint.com/HP/WCL /pigmt6.html#ciname) printed on the paint tube label), then connect these pigment markers to form the largest possible, straight sided enclosure (see examples below). The enclosed area is approximately the of the palette the range of hue and saturation that it is possible to mix with that selection of paints. The palette with the larger gamut will create a wider variety of color mixtures.



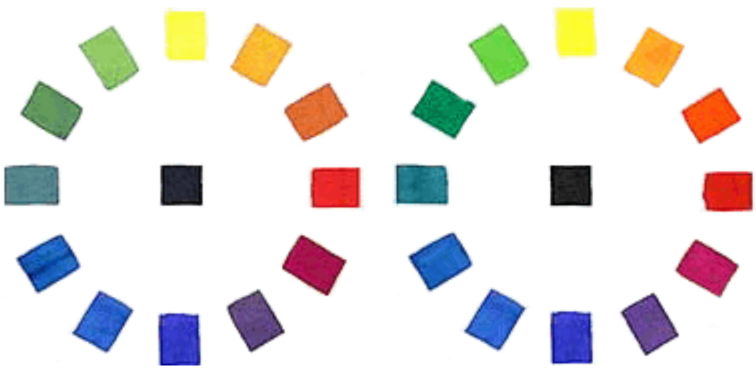
(http://www.handprint.com/HP/WCL/camwheel.html)

comparing the gamut of two palettes

split primary palette (left) and secondary palette (right) on the CIECAM a_Cb_C plane

This comparison shows that the split primary palette (at left) creates a lozenge of color mixtures that is skewed toward the "warm" colors of the palette, and creates dull mixtures in the greens and violets (the boundary lines of the palette pass close to the gray center in these hues). In contrast, with the more equally spaced secondary palette (http://www.handprint.com/HP/WCL/palette4e.html) (at right), we get a substantially increased range in color mixtures. This is because a single intense pigment anchors each primary and secondary hue, which pushes back the limits of the color space as far as possible (particularly on the green side).

The alternative (and better) way to compare palettes is to use each one to mix the twelve colors of a tertiary color wheel (http://www.handprint.com/HP/WCL/color13.html#tertiary). Display these mixtures either side by side or as matching paint wheels (http://www.handprint.com/HP/WCL/tech15.html) (below), and see what you get.



comparing paint wheels made with two palettes

split primary palette (left) and secondary palette (right)

This side by side comparison confirms the gamut differences identified with the palette schemes. The mixed red orange in the split primary palette (left) is so dull it is close to brown; the purple is dark and grayish, and the mixed greens are drab across the entire range. In contrast, the secondary palette (at right) is obviously much brighter in the greens, produces a more evenly saturated range of warm hues, and gets juicy purples as well.

The problem here is . Assuming two paints are both saturated to begin with, then the rule of saturation costs is: *the farther apart on the hue circle two paint colors are, the duller their mixture will be*. The obvious solution to saturation costs is to use a larger number of saturated paints, spaced equally around the hue circle.

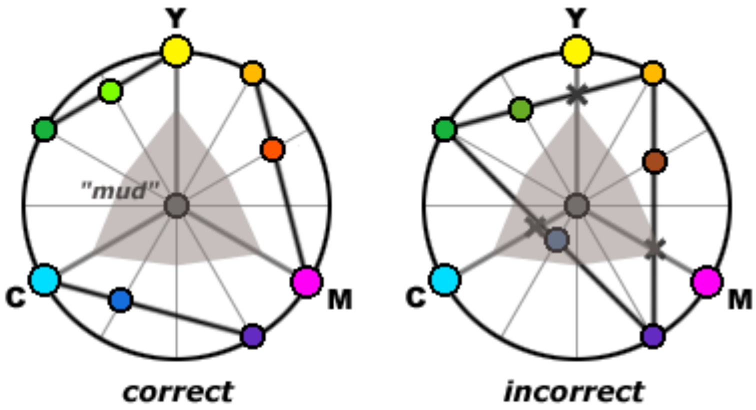
26. Given an arbitrary limit on the number of paints or inks in a palette, the largest variety of saturated color mixtures is obtained by choosing the most saturated pigments in hues equally spaced around the hue circle.

Choosing two paints or inks that are more similar in hue *does* increase the intensity of their mixture, as Chevreul says. But these saturation costs again have nothing to do with the contamination of one primary color with another. They appear even when we mix two monochromatic (single wavelength) lights that are completely free of tint by any other hue. In fact, mixing spectral lights was originally how Newton discovered (http://www.handprint.com/HP/WCL/color2.html#extraspectral) saturation costs, and devised the hue circle to explain them!

9. With a split primary palette, do not mix colors "across the line" of a primary color.

The modern prejudice in favor of high chroma color became potent in the late 19th and 20th centuries, and watercolor tutorials that advocated the split primary palette began to disparage dull color mixtures and warned painters to avoid them.

Among practitioners of the split primary palette, the "taint mixed with taint" rationale developed a complementary prohibition: do not mix colors on opposite sides of a "primary" color. This was called "crossing the line" and the mixture was called *"mud"*.



"crossing the line" in a split primary palette

In the examples, we mix the same *hue* of color (yellow green, orange or violet) using two split primary paints with the same "taint", or two primaries with a taint fromt the third primary. In each case, the result is a *duller* color mixture, a color closer to or even equal to "mud".

However, once the painter understands , and chooses paint colors that are equally spaced around the hue circle rather than split from the three primary colors, this prohibition is irrelevant. And certainly dull, dark colors are too often useful to prohibit them in painting styles the "mud" green in the diagram (above) is actually a handsome landscape foliage color.

27. "Mud" is a perjorative label for color mixtures that occur widely in nature and are indispensable in all historical and most contemporary painting styles.

Traditional color theory teaches color mixing *rules* and an antiquated, judgmental approach to color mixtures. Modern color theory teaches color mixing *skills* and the insights necessary to create whatever color is needed for any purpose.

10. Transparent watercolors achieve "luminosity" because light is reflected from the paper through the pigments, "like light through a stained glass window".

A very popular misconception in traditional color theory is that watercolors present a special "luminosity" that is due to the *stained glass* action of the watercolor pigments.

These two metaphors arose in the 19th century as part of the rivalrous disputes (http://www.handprint.com/HP/WCL/artist07.html) between watercolor societies or rather, between painters who used "muddy" gouache or body color, and those who insisted on using only "pure" transparent paints. Given the traditional color theory emphasis on color "purity", the churchly image of a stained glass window should arouse immediate suspicion. And, as I explain in detail (http://www.handprint.com/HP/WCL/tech16.html#transparencymyth) elsewhere, the metaphor is false.

If a pigment particle absorbs light to create , then that light is not available to be absorbed a second time. Light does not *pass through* a pigment particle it is either absorbed as heat, reflected as color or scattered as "white" light so light that is reflected from the painting to the viewer that has not been affected by pigment is only reflected from the paper.

This paper reflected light also does not pass through pigment particles, though it can hit a pigment particle on its way out. But this action will not be different from the light that is reflected from a gessoed canvas back through an acrylic or oil paint layer, so it can't be an advantage that watercolors have over other paint media.

In fact, watercolor paints *do not* form a paint layer, but scatter pigment particles around on the surface of the paper like gravel on a shag carpet (image, right). It's apparent in the photo that the paper fibers are as likely to scatter or block light as they are to send it back to the viewer, because **there is no paint layer in watercolors** the gum vehicle has dried around the fibers and pigment particles and sunk into the paper pulp.

Acrylic and oil paints do form a transparent layer. Light reflected within this layer *can* strike pigment particles twice, and has a greater chance of hitting a pigment particle once before it leaves the paint layer, which (along with reduction in white light scattering from the transparent binder surface) is why pigments in acrylic and oil paints can achieve a higher chroma than the same pigments in watercolors.

So what explains the special color appearance of a watercolor painting, or its apparent transparency? The fact, as shown in the photo, that so much bare paper can reflect light. This adds whiteness and *brightness* (luminance, not chroma) to the color, reducing the chroma and reducing the contrast ratio between the white and the darkest values. To see this contrast reducing effect more dramatically, hold a watercolor painting against the sun and observe light actually passing through the paper.

Watercolors also show the paper texture in the paint surface, instead of a shiny, obviously material layer, so that the image appears insubstantial and somehow floating in front of the paper. In fact, letting paint build up until it "bronzes" or acquires a shiny surface is considered a painting flaw. The visible paper surface, or the lack of visible paint layer, creates the impression of something transparent like a stained glass window, but it is not a special form of "luminosity".

28. The "luminosity" in watercolors arises from the reflection from the white paper, which reduces the contrast ratio and increases the brightness of the painting surface; it does not come from light *passing through* pigment particles.

The fixation of some watercolor painters on "transparent" pigments is also misdirected. *All pigments* can appear transparent, if they are diluted with enough water and applied as a smooth, seamless wash. Transparency happens *between* pigment particles. The key is to avoid a buildup of paint that appears as a paint layer (the real objection to gouache), or to soak the paper so much that the pigment particles migrate into the paper, where they are shadowed by the paper fibers.

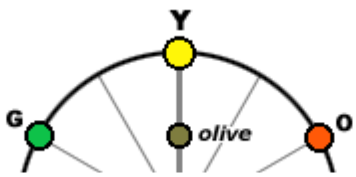
29. The "transparency" in watercolors is not in the pigments, but in the spacing between the pigment particles: opaque or "sedimentary" paints can be made transparent by diluting them, applying as a seamless wash, and avoiding paint buildup into a visible paint layer.

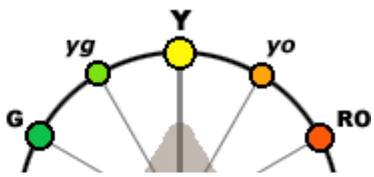
Use thick paint sparingly, and work as much as possible on dry or freshly wet paper, and you'll have all the "luminosity" you can handle.

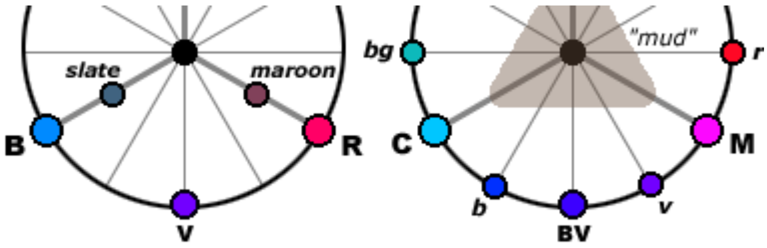
11. *Secondary* colors are 1:1 mixtures of two primary colors, and *tertiary* colors are 1:1 mixtures of two secondary colors.

Most of the hallmark concepts of traditional color theory have been antiquated by the progress in color science, colorant manufacture, media technologies and painting styles. A simple example is the change that has occurred in the definition of *tertiary colors*.

Traditional color theory starts with the three primary colors, secondary colors (http://www.handprint.com/HP/WCL/color13.html#secondary) are produced by the equal mixture of two primary colors. These are *orange* (**O**), green (**G**) and *violet* (**V**), as shown in the diagram (below).





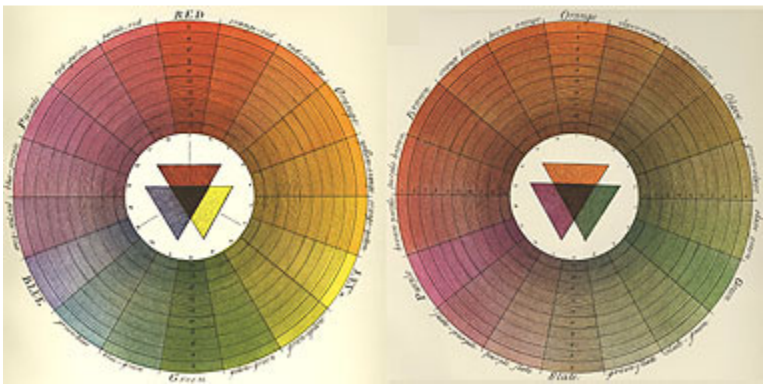


color theory tertiary colors

the traditional tertiary colors (left) and the modern tertiary hues (right)

In the traditional concept (based on the 18th century *red, yellow* and *blue* primaries), tertiary colors (http://www.handprint.com/HP/WCL/color13.html#tertdefs) are produced by the equal mixture of two secondary colors, which creates the three tertiaries *maroon* (dull red), *olive* (dull yellow) and *slate* (dull blue).

Dull color mixtures were fundamental to painting styles in 18th century painting practice so much so that the English entomologist Moses Harris (http://www.handprint.com/HP/WCL/color6.html#harris), in his *Natural System of Colours* (1766), devoted a separate color wheel to them, as mixtures of orange, green and purple (image, below).



the color wheels of moses harris (1766)

a 20th century reconstruction of the Harris color wheels; *(left)* mixtures of the "primitive" colors red, yellow and blue; *(right)* mixtures of the "compound" colors orange, green and purple

These traditional tertiaries anchored the useful dull color mixtures in relation to the primary colors, using secondary colors as a bridging framework. This integrative role of the traditional tertiary colors appears in the three alternative formulas for a tertiary mixture. The equal mixture of two secondary colors amounts to a 2:1:1 mixture of *all three* primaries, for example in *olive*:

2 O[1Y+1R] + 2 G[1Y+1B]=4 OLIVE [2Y+1R+1B]

Simply by rearranging the mixture components, we prove that the same tertiary color is equal to a 1:1 mixture of yellow and its complement, violet:

2 O[1Y+1R] + 2 G[1Y+1B]=2 Y[2Y] + 2 V[1R+1B]

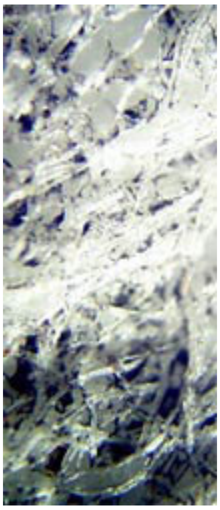
or to a 1:3 (!) mixture of a primary color with the darkest gray (near black) that can be mixed with the three primaries:

2 O[1Y+1R] + 2 G[1Y+1B]=1 Y[1Y] + 3 K[1Y+1R+1B]

... the last formula showing that the three traditional tertiaries are simply dulled versions of the three primary colors, creating a muted, dark, "minor key" primary triad palette.

This is all "in theory": to use these recipes in practice, we must have three primary paints of matching , which we get by first diluting the blue and red paints until an equal mixture with yellow produces an achromatic dark gray.

And there theory ends. We cannot duplicate these results by using these proportions in three primary paints out of the tube, and we certainly cannot get these results by using separate colors of yellow, orange, green, black and violet paint. For example, 3 parts carbon black will overwhelm 1 part yellow, and 1 part dioxazine violet will overwhelm 1 part yellow, because the black and violet are very dark and strongly tinting paints.



microscope image of an ultramarine blue wash on cold pressed watercolor paper

However, by the early 20th century, vast improvements in synthetic pigment manufacture, and the use of strongly saturated colorants in painting and advertising, had shifted the color theory emphasis to the circumference of the color wheel and to the most saturated version of all hues.

So in the modern concept (based on the 20th century *magenta, yellow* and *cyan* primaries), tertiary hues (http://www.handprint.com/HP/WCL/color13.html#tertiary) became the equal mixture of a primary hue and either of the secondary hues next to it. This creates the *six* tertiary hues *yellow orange* (**yo**), *red* (**r**), *violet* (**v**), *blue* (**b**), *blue green* (**bg**) and *yellow green* (**yg**). This has been the usage taught in the Famous Artists' Courses since the 1950's, and is the standard usage cited in the *American Heritage Dictionary of the English Language* (4th edition).

In modern color theory there is no need for the *tertiary* label, as a color in the "third rank" below *primary,* because we do not rely on primary mixtures to create them (instead artists use single pigment paints, and printers use spot colors); nor is there any need for *secondary* to describe "second rank" hues such as orange and green that are often more important and useful in painting than red violet or green blue.

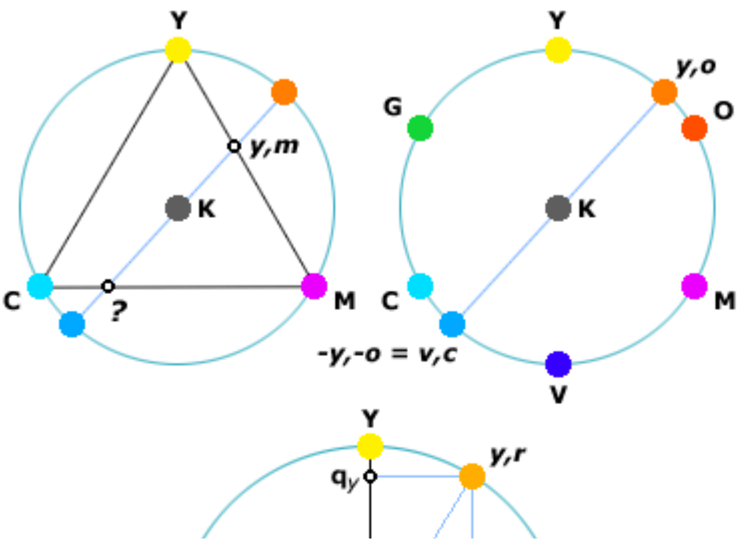
30. The designation of hues as "secondary" or "tertiary" has no relevance in modern color theory.

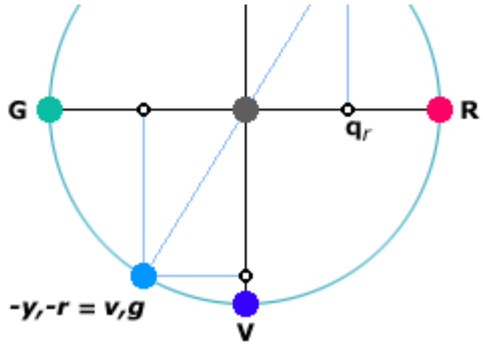
In place of these archaic labels, artists use the six basic hue categories and twelve compound hue categories to denote hues. There is no ranking of importance among hues; they are all equally important in color design.

12. Painters use the primary color framework to analyze visual colors and paint color mixtures.

There are two final misconceptions necessary to clear up. The first is that the traditional color theory framework is a powerful way for painters to think about conceptual colors, analyze visual colors, or guide paint color mixtures.

Analysis of Complementary Hues. Let's first test these claims on one of the central color theory preoccupations: identifying the to a given color for example, a yellow orange mixture (diagram, below).





identifying complementary hues

(top) using the traditional primary triad (left) requires insertion of secondary hues (right); (bottom) using the modern opponent dimensions

We start with the primary triad (**C**, **Y** and **M**), centered on the achromatic mixture (**K**) of all three primaries in equal proportions at equal tinting strength. We have created the most saturated possible yellow orange mixture from some quantity of yellow and magenta paint (**y,m**). What then is its visual or mixing complementary color (**C(y,m)**)?

Since any two complementary colors must mix to gray, the answer is simply to subtract the primary quantities in **y,m** from the **c,y,m** quantities in the achromatic mixture. To do that, we only have to make the larger of the two quantities in the **y,m** mixture equal to its quantity in the gray mixture. Thus, if we know that:

K = **20(C)** + **33(Y)** + **27(M)**
y,m = **60(Y)** + **40(M)**

then we standardize the larger quantity (60 parts of yellow) on the matching achromatic quantity (33 parts of yellow):

33/60 = **0.55**

we adjust the **y,m** proportions by that amount:

0.55*[60(Y) + 40(M)] = 33(Y) + 22(M)

and finally subtract those quantities from the achromatic quantities to get the complementary mixture **C(y,m)**:

C(y,m) = (20-0)(C) + (33-33)(Y) + (27-22)(M)
C(y,m) = 20(C) + 5(M).

Now, although Ogden Rood (http://www.handprint.com/HP/WCL/book3.html#rood) showed artists how to make similar calculations within a visual color triangle using mixture quantities from a color top (http://www.handprint.com/HP/WCL/colortop.html), I believe very few artists ever found their complementary paint mixtures by this kind of calculation!

That is because Moses Harris mooted the problem when he inserted the secondary or "compound" colors, the complements to the primary colors, in his color wheel. Now we are no longer working within a triangle but a circle, and the complement of the mixture **y,o** is the mixture **v,c** in the same relative proportions. And Harris explained that this is how his color wheel should be used (http://www.handprint.com/HP/WCL/color6.html#harris) *"if a contrast is wanting to any color or teint"*. The complementary colors get us out of the calculations: we judge colors visually instead.

Modern color theory goes one step further. It replaces the traditional primary/secondary framework with two opponent color dimensions, defined as visual hue relationships: *violet red/blue green* (**a+/a**) and *yellow/blue violet* (**b+/b**). These, along with a *lightness/brightness* (**J/Q**) or *white/black* (**W/K**) dimension, are the , descended by a long and indirect path from ideas first proposed by Evald Hering (http://www.handprint.com/HP/WCL/color2.html#heringtheory). They are more commonly known as the artist's primaries (http://www.handprint.com/HP/WCL/palette4d.html), and were the primary colors identified in the days before traditional color theory by painters such as Leonardo da Vinci (http://www.handprint.com/HP/WCL/color6.html#dyers).

In this color definition, the relative quantities of two visual primaries in a color ($\mathbf{q}_y$ and $\mathbf{q}_r$ for the **y,r** or yellow orange mixture) define, to a good approximation, the proportions of yellow and violet red *paints* of equal tinting strength that will create that hue as a material mixture. And these proportions are simply applied to the opposing primaries (in the example, *blue green* and *blue violet*) to mix the complementary hue.

However, with a modern artist's color wheel (http://www.handprint.com/HP/WCL/cwheel06.html) (the CIECAM a_Cb_C plane (http://www.handprint.com/HP/WCL/color7.html#CIECAMab)) even that indirection is not necessary. The hue plane is populated with hue and chroma markers for all important modern pigments used in art materials.

(http://www.handprint.com/HP/WCL/cwheel06.html)

click on image for a larger view (http://www.handprint.com/HP/WCL/cwheel06.html) click here (http://www.handprint.com/HP/WCL/cwheel06.pdf) for a full page, printer friendly (Adobe Acrobat PDF) version

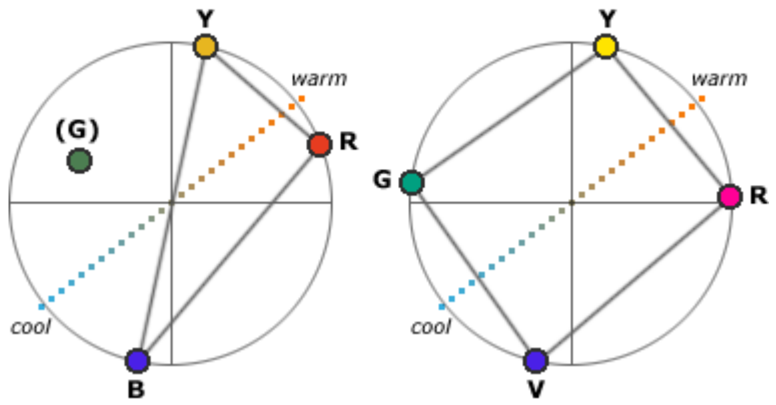
To print the color wheel, set page orientation
to "landscape" and print at 50% size or to fit an 8.5" x 11" sheet of paper.

Simply by from any chosen yellow orange pigment (color) through the "black" center of the color wheel and extending it to the opposite side, the artist locates the closest pigments to the visual complement of the chosen color, and can mix a perfect hue match from any two pigments on opposite sides of the line. Thus, the perfect visual complement of isoindolinone yellow (PY110 (http://www.handprint.com/HP/WCL/watery.html#PY110)) is ... cobalt blue (PB28), phthalo blue RS (PB15:1) or prussian [iron] blue (PB27).

31. The a+/a and b+/b opponent dimensions of modern perceptual color spaces are the most effective framework for analyzing complementary color relationships.

Consider, as an illustration, how the artist might analyze in the color design or color harmony in a painting.

The traditional primary triad palette (http://www.handprint.com/HP/WCL/palette4c.html) includes a red (**R**) such as cadmium red (PR108 (http://www.handprint.com/HP/WCL/waterr.html#PR108)) or alizarin crimson (PR83 (http://www.handprint.com/HP/WCL/waterr.html#PR83)) that contains more yellow than a violet red, and a blue (**B**) such as cobalt blue (PB28 (http://www.handprint.com/HP/WCL/waterb.html#PB28)) or ultramarine blue (PB29 (http://www.handprint.com/HP/WCL/waterb.html#PB29)) that contains more violet than a green blue. As a result, the primary palette is skewed to one side of the warm/cool dimension between *red orange* and *green blue;* yellow (**Y**) is the only color anchor above the line (diagram, below).



traditional and modern analysis of warm/cool contrast

(left) traditional RYB triad, plus green; (right) modern primaries

Which brings us to green. Traditional color theory does not usually explain the various ways to mix an orange or brown, or a violet or maroon but it always has quite a lot to say about *green*. And this is because green is necessary to balance color mixtures around the warm/cool axis.

In contrast, the modern primaries (**R**, **Y**, **G** and **V**) provide this balance naturally, and considerable nuance in varying color so that it is warmer either toward yellow or toward red, and cooler either toward green or toward blue.

The traditional color theory prohibition against using premixed greens, or having a green paint on the palette, is difficult to understand if one is concerned with either mixing convenience or color mixture variety. The prohibition against green pigments, or convenience green paints (http://www.handprint.com/HP/WCL/waterg.html#convenience) made with green pigments, is that they "pop out" of the primary triad as too chromatic or colorful.

32. Adding a green "primary" in concept, and use of a green paint in practice, is an efficient and accurate framework for color analysis and paint mixing that is sanctioned by a long painting tradition.

Medieval painters, supposedly encumbered by the false Aristotelian theory of colors, understood this clearly, because they remained much closer to their materials. For example, the common portrait painting method was to lay down the modeling of a face in a dull green paint, such as *terre verte,* then apply a glaze of transparent carmine. The result, which is striking the first time you try it, is that the color blossoms into a beautifully glowing dull orange or deep yellow tone.

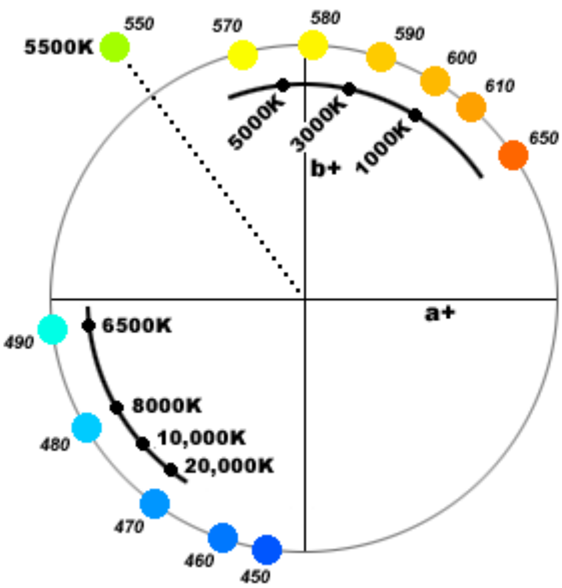
This dynamic arises because the eye is adept at compensating for colored illumination (the illuminant) if it exists, or imputing colored illumination to an image if the color balance appears limited or skewed in some way. Because traditional color theory assigns a separate set of "primary" colors (or **RGB**) to the eye and the eye's response to light, radiant color is detached from material color in a completely unnatural way.

Here for example is a painting of hands made entirely in red and green paints (excepting the yellow and blue accents in the colored bracelet): the pure paint colors (slightly different for the hands and table background) are presented in the dowels inset into the table surface.

a painting made entirely of red and green paints (except for the bracelet); party chick by Bruce MacEvoy © 2006

How is it possible to mix a satisfactory painting using only two colors? Simple: the eye supplies the "missing" color! We interpret the painting as representing a pair of pale hands under a "cool" greenish or bluish illuminant (color of light), not as a pair of ghoulish green hands under a "white" illuminant. Finally, the concern with the subtractive primary triad distracts painters from It's really the *eye,* not the paints, that provides the color in a painting.

I describe elsewhere (http://www.handprint.com/HP/WCL/color12.html#wcequalsyb) the color transitions produced by natural changes in daylight, weather and time of year, and the color transitions in incandescent artificial light. When defined as correlated color temperatures (http://www.handprint.com/HP/WCL/color12.html#cct), these conveniently fit within the modern primary framework where they can be matched to specific paint hues.



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)

Because chromatic adaptation (http://www.handprint.com/HP/WCL/color4.html#chromaadapt) occurs through changes in the eye's **RGB** color sensitivity and through rebalancing of the **ab** opponent dimensions, the modern primaries are a better framework than the traditional **RYB** or modern **CYM** subtractive primaries for analyzing the eye's response to landscape and light.

33. Because the adaption of the eye to natural light is organized around the a+/a and b+/b dimensions, the modern primaries provide a comprehensive framework to analyze the relations between illumination, visible color and paint mixture.

We have identified the two fundamental problems with 18th century color theory: a **failure to embrace materials** as the focus of artistic understanding, and a **misunderstanding of color perception** that begins with the idea of "color in the light" and extends to the geometry of color relationships. These are not complications or obstacles to a modern color theory: they demonstrate that color theory has for centuries been talking about color in the abstract, as conceptual colors and ideal color mixtures. But color is not only a specific sensation, it is also always in part a specific stimulus a specific material, or a specific mixture of lights.

additive & subtractive color mixing

The previous section has confronted the most important color misconceptions foisted on painters by traditional color theory. Now we start the process of building a modern color theory, beginning with color mixture.

Painters mix their paints to shape the light reflected from a painting, and the viewer's eye interprets this reflected light as color under light in space. These two extremes of color experience the mixed paints, and the interpreting eye are described by two separate and unequal color mixing theories, explained in full in the page additive & subtractive color mixing (http://www.handprint.com/HP/WCL/color5.html).

There are two surprises when we learn about color mixture. The first is that subtractive color mixture is nothing more than additive color mixture, in an expanded form that tries to compensate for the light absorbing effects of material mixtures.

The second is that additive color mixture is a rigorous explanation of color vision, a true scientific theory; but subtractive color mixture is only an idealized and unreliable approximation of the actual complexity and diversity of material color mixture.

Additive Color Mixing. **Additive color mixing** explains *how the eye interprets light wavelengths* in the perception of color.

Additive mixture is always based on *four* primary colors, called the four cardinal lights (http://www.handprint.com/HP/WCL/color6.html#whitepoint). These are most commonly red orange, middle green, blue violet, and the white light defined by mixing all three colored lights together. The white light defines the relative brightness or tinting strength of the three chromatic lights, so that they can be used to define color mixtures precisely.

This trichromatic foundation (http://www.handprint.com/HP/WCL

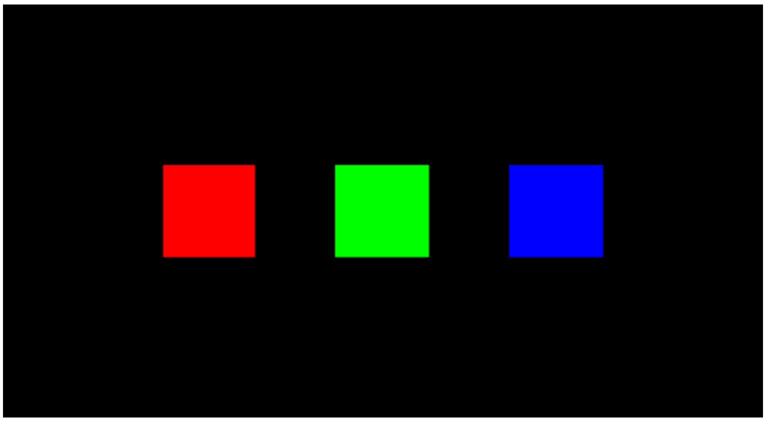
/color6.html#helmholtz) is in turn the basis for all modern chromaticity diagrams (http://www.handprint.com/HP/WCL/color1.html#chromaticity), the identification of visual complementary colors (http://www.handprint.com /HP/WCL/color13.html#compprobs), and the definition of modern trichromatic color models (http://www.handprint.com/HP/WCL/color7.html#CIECAM).

Additive Mixtures Occur In The Eye. The beauty of additive color mixing principles lies in their narrow scope. They focus on a single sensory process the average or typical responses of the L, M and S photoreceptors (http://www.handprint.com/HP/WCL/color1.html#receptors) to light for the explanation of color mixtures.

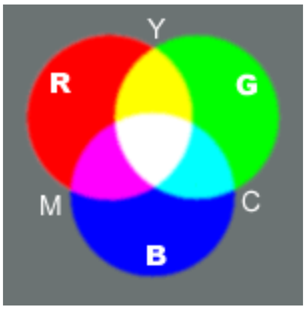
But wait ... isn't additive color mixture really a theory of how *light* mixtures behave? No, it is not. This misconception arises because light is obviously the only stimulus that the eye responds to, and because lights of various colors are explicitly manipulated in color matching experiments (http://www.handprint.com/HP/WCL/color6.html#colormatching) used to measure additive color mixtures. But light is the stimulus, and **additive color mixing describes the *response* of the eye to a light stimulus**.

The RGB Additive "Primary" Lights. How do we illustrate, verify or measure the rules of additive color mixing? Obviously, by manipulating the outputs of the separate **L**, **M** and **S** cones. How do we manipulate these outputs? By stimulating them with **three colored lights red, green, and blue violet** (abbreviated **RGB**). Necessarily, these lights create a fourth "primary": the "white" light mixture (http://www.handprint.com/HP/WCL/color6.html#whitepoint) of them all.

The image below displays the "primary" RGB colors of your computer monitor. Note that the green primary contains too much yellow, and the blue primary not enough violet, which dulls the purple and blue green mixtures, and sharply reduces the number of visually different green mixtures possible on a computer monitor.



The illustration (below) shows the typical demonstration of additive light mixtures, made by shining three overlapping circles of filtered light onto an achromatic (gray or white) surface. If the surface is illuminated by both the red and green lights, but not by the blue light, then the eye responds with the color sensation of yellow. A magenta color results from the mixture of red and blue violet light, and cyan from the mixture of blue violet and green. In additive color mixing, yellow and blue don't make green they make white!



additive color mixtures

as demonstrated with filtered lights; note that each pair of RGB primaries mixes one of the subtractive (CYM) primaries

It's handy to think of additive mixing as **the "white" color theory**. Mixing light wavelengths from the "red," "green" and "blue violet" parts of the spectrum **adds**

luminosity and negates hue to shift the mixture color of lights from dim pure hues toward bright whites.

The key principle is that the eye always *adds together* all the wavelengths of light incident on the retina nothing is lost and it is this total light sensation that the eye interprets as color.

The foundation of additive color mixing is called trichromatic metamerism (http://www.handprint.com/HP/WCL/color6.html#metamerism): the color produced by any combination of light wavelengths, no matter how complex it may be, can be exactly matched by the visual mixture of no more than three lights. The match can be created with three strongly saturated (single wavelength or monochromatic) lights, or at most two monochromatic lights mixed with a "white" light. **All physically possible light colors can be reduced to a specific mixture of at most three lights**.

This additive behavior leads to an important constant in color vision: **the chromaticity and brightness of lights predicts the chromaticity and brightness of their mixture** for moderately dim to bright lights. This is true regardless of whether the lights are monochromatic (a very pure hue, as we see in a single wavelength of light) or complex (such as daylight).

We will discover that equivalent *subtractive* metameric rules in the many kinds of radiant color mixing, and that lack of predictable consistency in substance mixtures is the most important difference between additive and subtractive color mixing.

As you may have guessed by now, the distinction between *conceptual colors* and *material colors* also appears in the difference between the invisible and therefore conceptual *visual primaries* (the **L**, **M** and **S** cone responses) and the light mixtures used to demonstrate or measure our color sensations.

The True Additive Primaries Are Invisible. The diagram at right shows the location on the CIELUV chromaticity diagram (http://www.handprint.com/HP/WCL/color7.html#CIE1976uv) of three monochromatic lights (at 460nm, 530nm and 650nm) that have frequently been used in color vision research to analyze trichromatic color matches and opponent color mixtures.

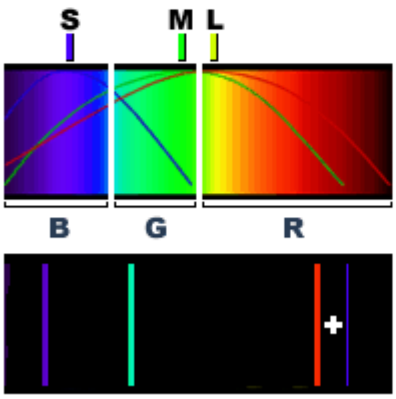
The focus here is on the white triangle or gamut (http://www.handprint.com/HP/WCL/color13.html#gamut) that connects the three primary lights. This defines the range of actual additive color mixtures it is possible to make with those three primaries. This gamut encloses most, but not all, of the chromaticity area, which defines the area of *all physically possible* light colors. A significant portion of the chromaticity diagram is outside the gamut. In other words, **the visible RGB primary lights cannot mix all colors**.

Thus, the "green primary" gives full mixing coverage along the red to yellow colors, but it cannot mix (with the "blue violet" primary) the most intense greens, blue greens and blues. In addition, the "blue violet" and "red" monochromatic primaries cannot mix the most intense purples and red violets.

The true additive primaries, the only "primaries" that can mix all possible colors, are the outputs from the **L**, **M** and **S** cones. We are never aware of these outputs directly and therefore they are invisible. We only experience them as the tendency toward a red, green or blue color sensation that results from the combination and interpretation of these outputs in the visual cortex.

How Do We Choose the RGB Lights? Some artists believe that the RGB primary lights are the same hues that most stimulate the three receptor cones. This is false. The cones are actually most sensitive (http://www.handprint.com/HP/WCL/color1.html#normconesens) to "green yellow" (**L**) "green" (**M**) and "blue violet" (**S**) wavelengths, as shown below.

wavelengths of maximum sensitivity



lights used to demonstrate additive mixing

additive primary colors are illustrative only

the wavelengths of maximum sensitivity for the **L**, **M** and **S** cones (top) are unrelated to the colored lights used to simulate the cones in additive color mixing demonstrations (bottom)

Red, green and blue violet lights are used by convention and convenience, and it is from these color matching lights (http://www.handprint.com/HP/WCL/color6.html#colormatching) that we get the names red, green and blue assigned to the additive primaries.

There's a simple logic for choosing these primary lights. Almost any light wavelength that stimulates one cone will also stimulate one or both of the other cones, because the cone sensitivity curves (especially **L** and **M**) overlap (http://www.handprint.com/HP/WCL/color1.html#logconesens). To explain color mixing as the result of three *independent* types of photoreceptor response, we need three light wavelengths that each stimulate one cone *much more* than the other two. In other words:

34. An ideal additive primary color must stimulate only one type of receptor cone (L, M or S) as strongly as possible, and stimulate the other two types of cone as little as possible.

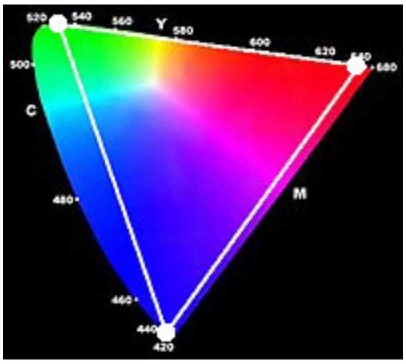
35. The optimal choice of physical lights for additive color media are typically orange red (R), green (G) and violet blue (B).

So, within each section of the spectrum (http://www.handprint.com/HP/WCL/color3.html#howread) where the **L**, **M** or **S** cone is the dominant receptor, we pick a wavelength that creates the *greatest difference in response* between that cone and the other two.

Does Additive Mixture Require RGB Lights? Many artists believe that red, green and blue violet lights *must* be used to explain or demonstrate additive color mixing. Again, not true. The choice of lights is arbitrary, and one selection of primaries is better than another only if we require the mixture gamut to be as large or comprehensive as possible.

We could just as easily demonstrate additive color mixing with colored lights representing the subtractive primary colors cyan, yellow and magenta, although most of the blues, greens and reds that we could mix with these lights would appear quite whitish or unsaturated.

The somewhat arbitrary procedures for choosing the additive primary lights are acceptable because the real lights are not the actual basis of additive color mixing. **The true additive primary colors are the photoreceptor outputs.** We use **RGB** colored lights to *symbolize* the **LMS** receptor outputs, because they are also the most effective way to *manipulate* those outputs.



the gamut of RGB primaries
used in color vision research

additive light mixing gamut defined by lights at 460, 530 and 650 nm

A Scientific Theory of Color Vision. For many centuries, the behavior of color mixtures was difficult to explain because material color, which seemed to be anchored in "real" objects of the external world, was conceptually distinguished from the "illusory" colors in rainbows or prisms. The two types of mixtures behaved differently, but the reason for the difference was unknown.

The trichromatic theory provided the clarifying explanation and prediction of all color sensations as arising in the behavior of the eye. Because the **L**, **M** and **S** receptor responses can be predicted mathematically from the summed intensity of all wavelengths in a light stimulus, the additive primaries empirically connect a measurable light stimulus to a measurable (matchable) color sensation at least, in experimentally restricted viewing conditions. This is what makes additive color mixing, in the *scientific* sense of the word, a *theory* of color vision.

Subtractive Color Mixture. Subtractive color mixing is, in comparison to , a flawed and approximate attempt to describe the colors that result *when light absorbing substances are mixed*.

The principles of subtractive color mixture are not a rigorous theory at all. They are a description of the way colors *should mix* in the ideal case which never occurs.

Subtractive mixing theory imitates the main features of additive color theory, and to understand the problems with subtractive color mixing, we need to unmask these points of imitation one by one.

Subtractive Mixtures Occur in Substances. First, let's get clear on what subtractive mixing rules are trying to explain. **All subtractive color mixing occurs in the external world**, in a wide variety of *material colors*.

In principle, subtractive color theory ought to be able to explain the color changes that occur in *any kind of material mixture*. It also ought to explain the color changes that occur when a surface is illuminated by different illuminants (http://www.handprint.com/HP/WCL/color10.html#surfaceshadow) (colors of light). And this is the fundamental difficulty with subtractive mixing theory: **it must explain the behavior of too many different substances**.

This problem does not arise in additive color mixture, thanks to in lights. Even though two colored lights may be constituted from very different combinations of light wavelengths, so long as the two lights have exactly the same color, they will behave exactly the same in all mixtures with all other lights.

In subtractive color mixture, exactly the opposite is true: even when two materials have exactly the same color, they may not behave the same in mixtures with other materials.

This problem is minimized, but hardly eliminated, by limiting the application of subtractive mixing principles to manufactured colorants. Even here, the variety of materials includes light reflecting substances (such as powders, paints, dyes or inks) and light transmitting substances (such as photographic filters, stained glass or tinted liquids).

I give the name **substance uncertainty** to this unpredictable connection between a material's physical attributes and color mixing behavior, and I explore the depth of this problem in the .

For now, the essential point is that **we cannot use the measured color of two**

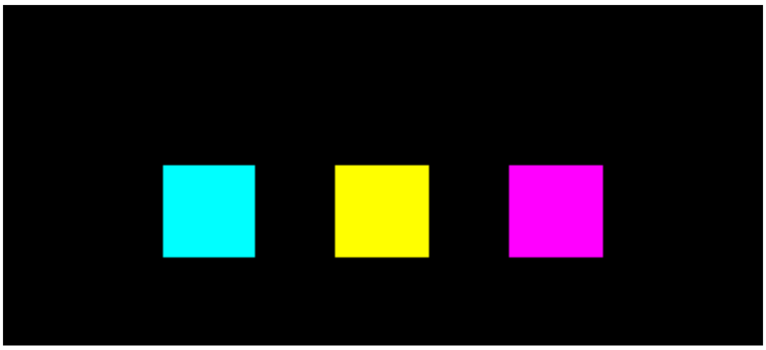
paints to predict the color of their mixture. This is the most important point of difference with additive color theory, where the measured color of two lights of moderate brightness *can* accurately predict the color of their mixture.

The CYM Subtractive "Primary" Colors. Subtractive color mixtures have been recognized and used in dyers' and painters' trades since ancient Greece (http://www.handprint.com/HP/WCL/color6.html#aristotle). That long trial and error practice fixed on *red, yellow* and *blue* as the subtractive primary colors. This attained the status of a commonly accepted "color theory" in the 18th century (http://www.handprint.com/HP/WCL/color6.html#materialtrichromacy).

In fact, the traditional choice of primary colors was limited by the historical availability of suitable pigments, which until the late 19th century (http://www.handprint.com/HP/WCL/book2.html) were comparatively dull and dark. these traditional subtractive primaries are relicts of traditional color theory.

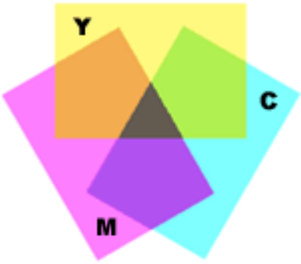
Color choices today have been greatly expanded by modern industrial chemistry (http://www.handprint.com/HP/WCL/pigmt1d.html), so that the modern **subtractive "primary" colors are cyan, yellow and magenta** (abbreviated **CYM**)

Here are exemplars of the three subtractive primaries in your computer monitor colors.



[redacted]

There are many different material demonstrations of subtractive mixture, but one of the most common and convenient is to overlap different colored filters on a brightly lit white background or diffusing panel, as illustrated in the figure below.



subtractive CYM color mixtures

as demonstrated in overlapping sheets of transparent colored plastic (transmission or filter mixture)

These primaries produce the mixtures familiar to us in paints. When we mix together a yellow and magenta (http://www.handprint.com/HP/WCL/color13.html#mixwarm) paint, the resulting mixture is scarlet or orange; the mixture of magenta and cyan (http://www.handprint.com/HP/WCL/color13.html#mixcool) yields purples and blues, and green result from the mixture of yellow and cyan.

However these subtractive cyan, yellow and magenta primaries are presented as the basic or elemental *conceptual colors* in subtractive color mixing, no matter what kinds of *material colors* in paints, inks, dyes, pigments or filters are used to actually mix those colors.

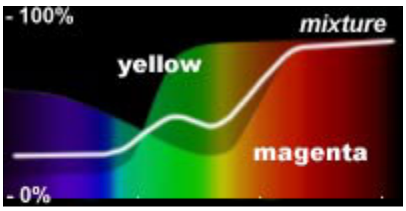
So we have to ask: what is the *universal* visual effect on color that happens when we mix material substances? What is *primary* about subtractive "primary" colors?

Subtractive Mixtures Always Increase Light Absorptance. The first step to an answer is this: when we combine paints, dyes or filters, we do not increase their light reflecting (or transmitting) behavior but their *light absorbing behavior*.

A subtractive mixture absorbs all light wavelengths that *each* colorant absorbs by itself. Subtractive mixture always increases the darkness of material colors; if we mix a white paint with a green paint, the white paint is darkened as a result. If additive mixture is the "white" color theory, then subtractive mixture is **the "black" color theory**.

Mixing all three subtractive primaries produces a dark neutral, the opposite of white, because each paint **subtracts or absorbs light** that might be reflected by the other. Subtractive color mixtures can only be made lighter by diluting the amount of pigment in the mixture with white paint or water; either remedy weakens the color saturation. So subtractive mixture almost always also reduces the hue purity (increases the grayness) in the mixture color.

Multiplicative Darkness Mixture. Well, *how* do colors combine in subtractive mixtures? This is always some form of multiplication or *product* of the separate reflectance curves (http://www.handprint.com/HP/WCL /color3.html#reflectance) (as shown below for two paints labeled magenta and yellow).



subtractive color mixing of yellow and magenta

white line shows reflectance curve of subtractive mixture; high reflectance remains only where *both* paints reflect light

In this mixture, the yellow absorbance subtracts light from the "blue" reflectance in magenta, and the magenta absorbance destroys the "green" reflectance in yellow. The common reflectance, the light reflected by *both* paints, is largely in the "red orange" and "red" part of the spectrum, which is the approximate hue of the mixture. It is specifically this **mutual antagonism among light absorbing substances** that subtractive color mixing tries to explain.

This mutual antagonism depends on many physical attributes of the colorants, in particular (for pigments) on their tinting strength, particle size and hiding power (see this of paint physical attributes). In general, pigments that have a higher tinting strength, smaller particle size and greater hiding power (opacity) will have a "weight" or impact in mixtures that is greater than their physical proportion in the mixture.

However, as a general rule for most paints and dyes in most applications, the reflectance resulting from a physical mixture of pigments is usually close to the geometric mean (http://www.handprint.com/HP/WCL/color3.html#mixprofile) of the separate paint reflectance curves *across each wavelength in the spectrum*. (The geometric mean of two numbers is the square root of their product.) For example, if a white paint reflects 98% of the light at 452nm, and a black paint reflects 10% of the light, their mixture (in equal proportions at equal tinting strength) will reflect approximately 31% of the light at that wavelength.

We have to use a different mixing rule for filters, where the mixture color is usually equal to the *product* of the separate transmission profiles. That is, two filters that separately transmit 98% and 10% of a wavelength will transmit about 9.8% of the light when they are combined.

When we apply these mixing calculations to the reflectance or transmission profiles, we find that the mixture profile is always **closer to the darker profile** in the combined total reflectance curve, or **darker than the darker profile** in the combined total transmission curve. Mixing white and black in equal proportions does not reduce the luminance of white by half, but by more than two thirds (in paints) or up to 100% (in filters).

One result is that sequentially (transmissively) combining two filters *always* results in a darker mixture than physically mixing the filter colorants as paints; and physically (subtractively) mixing two colorants *always* results in a duller, darker color than visually (additively) mixing the same colorants, for example on a color top (http://www.handprint.com/HP/WCL/colortop.html).

Double Cone Stimulation. We've identified the blackening and multiplicative effects of subtractive color mixtures, but we still haven't identified the attributes that define the subtractive primary *colors* cyan, yellow and magenta. What is the material attribute of "yellowness" that occurs in all yellow colored *materials*?

The answer begins with the fact that subtractive mixtures always destroy ("subtract") the material luminance, making color both darker and duller. To compensate for this, painters should start with **colors that are both *light* and *bright*** light valued *and* highly saturated.

If we experiment with various light valued, high chroma colorants, as the ancient painters and dyers did with their much duller and darker pigments, we discover that some do much better than others as subtractive primary colors. Why? Because the key to subtractive primaries is not in their light value or high chroma alone. It's in how that color intensity affects the eye:

36. An ideal subtractive primary color must stimulate two types of receptor cones (L and M, or L and S, or M and S) as strongly and equally as possible, and stimulate the third type of cone as little as possible.

In other words, the subtractive primaries are only *an indirect way* to specify the **L,**

M and **S** cone responses of additive color mixing!

Traditional color theory texts often express this point in negative terms, saying that each subtractive primary *absorbs or "subtracts"* from "white" light the wavelengths representing a single additive primary. This principle is often expressed as four subtractive formulas, including both white (**W**) and black (**K**):

C = W R
Y = W B
M = W G
K = W (R + G + B)

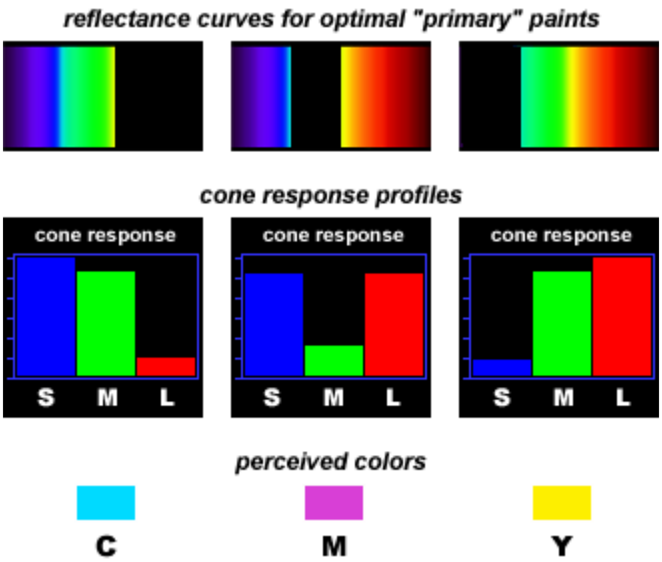
Thus cyan paint (**C**) subtracts "red" light (**R**) from the total "white" (**W**) light spectrum; magenta paint (**M**) subtracts "green" (**G**) light from the spectrum, yellow paint (**Y**) subtracts "blue" (**B**) light; black paint (**K**) subtracts all light from the spectrum.

This way of defining subtractive primaries is inaccurate, both because it implies the wrong complementary hues (yellow is not the complement of blue, and red is not the complement of cyan), and because it allows for dull and dark "primary" colors. Thus, raw umber almost completely absorbs "blue" light, and iron (prussian) blue almost completely absorbs "red" light, so they *can* be used as a primary yellow and blue, even though they also absorb light from other parts of the spectrum and therefore appear relatively dull or dark.

Ideal Subtractive Primaries. The better way to define subtractive primary colors is to specify the conceptual color that produces the maximum possible stimulation in two types of cones and the minimum possible stimulation to the third type of cone. Then we can simply choose the colorants that achieve those receptor effects as far as possible with a material color.

We define the conceptual color by means of an *ideal* (conceptual) reflectance profile, called an optimal color (http://www.handprint.com/HP/WCL/color3.html#optimalstimuli). Optimal colors always have the *maximum possible saturation* or hue purity of any surface color at a given hue and lightness, and the *maximum possible lightness* of any surface color of a given hue and saturation. So they are the perfect "light, bright" colors we want for our ideal subtractive primaries.

The diagram below (top row) shows the spectral reflectance curves and cone responses produced by these three idealized subtractive primaries.



ideal spectral reflectance curves for subtractive
primary colors

each subtractive primary reflects or transmits the light representing two additive primary colors

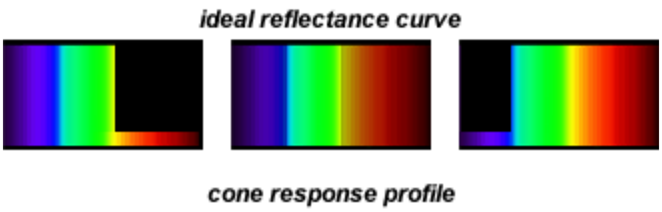
In the top row of the figure are the *reflectance curves for optimal primary paints*. The *cone response profiles* (middle row) show how these optimal subtractive primaries affect the **L**, **M** and **S** cone outputs. The bottom row shows the *perceived colors* that result from the cone responses in additive color mixing.

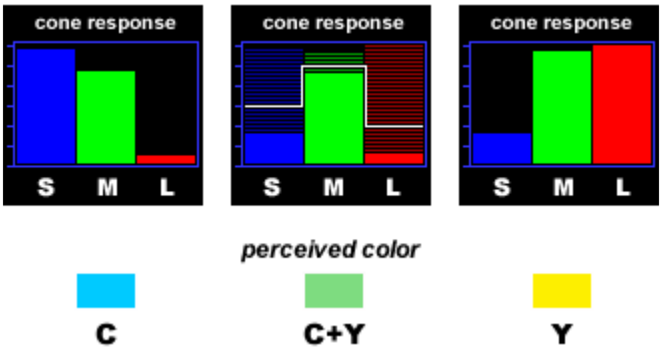
Observe, in the ideal cone response profiles above, that all three *physically ideal* subtractive primaries stimulate to a significant degree the third or "unwanted" **L**, **M** or **S** cone. (Note in particular the **M** response in magenta.) In each case we cannot achieve a visually pure primary hue of paint, because of a *physiological* limitation: the overlap between the **M** cone and **L** cone fundamentals (http://www.handprint.com/HP/WCL/color1.html#logconesens). We just can't stimulate the **L** cone with "red orange" light, or the **S** cone with "blue violet" light, without also stimulating the **M** cone, just as if we stimulated it with "green" light.

It is instructive to compare the chromaticity of these ideal subtractive primaries with the chromaticity of common pigment choices for subtractive primary colors in watercolor paints or printing inks, as . We see that artists do not use the "ideal" primary colors, and for a variety of practical reasons: a colorant matching the ideal hue is not available, or its physical attributes (lightfastness, chroma, lightness, transparency, tinting strength) are inadequate, or its mixtures with other "primary" colorants lack the saturation desired for the specific printing or painting purpose.

Mixing Subtractive Primaries. Finally, what happens when these ideal primary paints are mixed?

Because any two subtractive primaries will share reflectance in either the "red," "green" or "blue" wavelengths associated with a single additive primary color, **any two subtractive primaries share reflectance that stimulates a single photoreceptor**. Yellow and magenta share "red" reflectance that stimulates the **L** cone, yellow and cyan share "green" reflectance that stimulates the **M** cone, and magenta and cyan share "blue" reflectance that stimulates the **S** cone.





mixing two ideal subtractive primary colors

reflectance representing a single additive primary remains high; other parts of the spectrum also reflect light (white line shows cone response to a 50:50 paint mixture), and this flatter cone response profile is perceived as a grayer color

However, in any subtractive mixture, **the remaining two additive primaries must compete with each other**. As shown above for the mixture of yellow and cyan, the "red" light that primarily stimulates the **L** cone is reflected by yellow but absorbed by cyan; the "blue" light that stimulates the **S** cone is reflected by cyan but absorbed by yellow. So both are substantially darkened. Like a seesaw, as "blue" reflectance goes up, "red" reflectance goes down, and vice versa.

These tradeoffs also mean that **mixtures of two subtractive primaries reflect light from all parts of the spectrum**. The result is a flatter cone response profile (shown in the middle diagram of the figure), which creates the perception of a less saturated color mixture a color closer to gray. This is of course the saturation cost (http://www.handprint.com/HP/WCL/color14.html#satcost) in subtractive mixtures the tendency of paint mixtures to be darker *and* duller than the original paints.

37. The choice of appropriate subtractive primary pigments depends on the variety of colorants available in a given medium, their price and physical attributes, and the range of colors in the image to be reproduced.

These saturation costs the unwanted third cone stimulation in ideal colors and the added "white" reflectance in real colors are the fundamental reason why **material primary colors are always imperfect**, as explained here (http://www.handprint.com/HP/WCL/color6.html#imaginary). There is no combination of three material primary colors in any medium (dyes, paints, phosphors, filters) that can mix every possible color in that medium.

Don't Confuse Additive & Subtractive Mixtures. I hope you now understand why *all* color mixing involves the retinal response to light; the only issue is whether or how we let material substances interfere with our control of the light that reaches the eye.

Because subtractive color mixing (in materials) is actually an indirect manipulation of additive color mixing (in cone responses), the two types of color mixture can be **demonstrated in superficially similar ways.** To avoid confusion, remember that the fundamental difference is whether light wavelengths are excluded by the colored substances before the light reaches the eye (the light mixing occurs in the external world), or light wavelengths are separately able to reach the receptor cones (the light mixing occurs in the eye).

With **colored transmission filters**, the additive color mixing demonstration is produced by placing a colored yellow filter over one beam of white light, and a blue filter over a second beam of white light, then overlapping the two colored beams on a reflective surface. Because each filter is placed over a *separate beam of light,* the blue and yellow lights are both reflected to the eye, where they both affect the receptor cones to create the sensation of "white" light. In contrast, the subtractive color mixing demonstration is produced with the same yellow and blue filters, this time *both placed over a single beam of light*. The two filters then act in combination to absorb light before it ever reaches the eye; the only wavelengths that can pass through both filters at the same time are in the "green" section of the spectrum, so green is the color we see.

With **paints or inks**, the additive color mixing demonstration is produced by spinning the two paints on a color top (http://www.handprint.com/HP/WCL/colortop.html), or by printing the two colors as closely spaced dots in halftone color printing. In either case, each color of paint can still separately reflect light to eye, even though they are optically blended through motion blurring or visual fusion (http://www.handprint.com/HP/WCL/color8.html#visualfusion). When they are physically mixed as paints or inks, they cancel reflectance in each other to produce a subtractive color mixture.

Finally, it should be clear why **red and blue are not subtractive primary colors**. A red paint (http://www.handprint.com/HP/WCL/IMG/RC/red.html) reflects light only from the "red" end of the spectrum; it stimulates primarily the **L** cones, but not the **M** or **S**. Most blue paints (http://www.handprint.com/HP/WCL/IMG/RC/blue.html) reflect mostly "blue" and some "green" light, stimulating the **S** and **M** cones, but not the **L**. So their mixture creates a very dull purple, because the two colors have no reflectance in common: most wavelengths reflected by one color are absorbed by the other.

The same considerations explain why the **RGB** additive primaries are effective only in light stimuli, such as televisions or computer monitors, but not in paints or inks. There is no shared reflectance in the reflectance curves of red orange, green and blue violet paints, so these produce very dull, dark colors when mixed subtractively. The additive primaries are only effective when the mixing occurs in the retina.

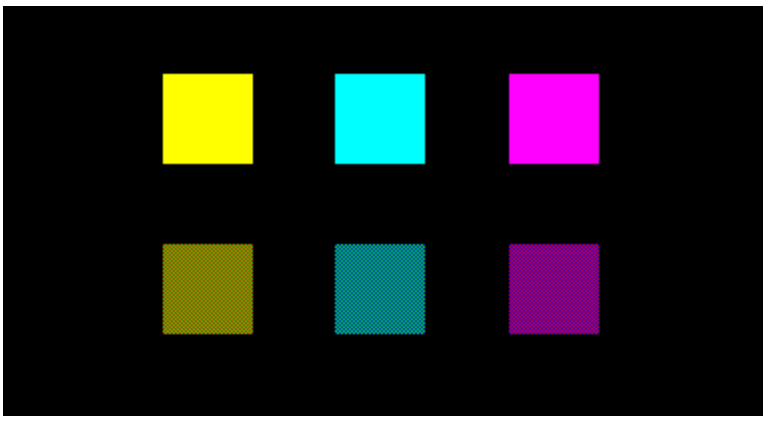
By the same token, the **CYM** primaries are ineffective in televisions or computer monitors. There is a large overlap in the emittance curves of cyan, yellow and magenta lights, so that their additive light mixtures appear whitened and bright the equivalent of dark and dull in subtractive mixing. The subtractive primaries are only effective when the mixing occurs in materials.

Partitive Mixture. Finally, there is a hybrid case of color mixture that occurs in an image composed of small, separate but closely crowded color dots or pixels that are perceived by the eye as a visually continuous color area. Exploring this technology will clarify further the differences between additive and subtractive color mixture.

The text and every image in this web page is generated on your color monitor by thousands of tiny **RGB** lights that are too small for the eye to resolve optically or retinally: the eye blends them together as a textureless surface. This visual fusion (http://www.handprint.com/HP/WCL/color8.html#visualfusion) is also the reason why homogeneous color areas appear from a field of halftone or overlapping colored dots in printed books and magazines, and smooth colors appear from the millions of tiny dye molecules impregnated in color photographic papers.

However, computer monitors use **RGB** primaries to create color mixtures, but all photographs and printed color images use the **CYM** subtractive primaries instead. So the question arises: why aren't the additive **RGB** primaries used in printing and photography just as they are in computer monitors?

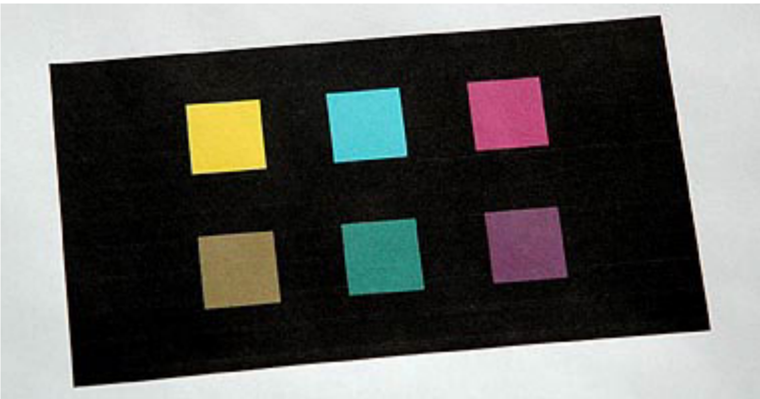
To grasp the answer, it will help first to print the diagram below on your color printer.



the subtractive primary colors as additive RGB lights and as additive RGB pixels

In this image, the **CYM** color areas in the upper row are actually created on the computer monitor by the visual fusion and additive mixture of two of the three **RGB** *monitor lights*. These are physically distinct but too small for the eye to resolve into a dot pattern.

The color areas in the lower row are created by the visual fusion of alternating **RGB** *pixels*. Each pixel contains three monitor lights, so this doubles the amount of black (unilluminated) area within each color. (Examine the two areas with a magnifying glass.) This doubled black spacing between lights coarsens the screen texture enough to make it visible.



the subtractive primary colors as pure CYM inks and as additive RGB halftone dots

The printed copy looks quite different, especially in the yellow (image above). The printer has silently substituted a pure yellow ink for the "yellow" **R**+**G** monitor light mixture. However your computer screen is fundamentally a light source, despite the illusion (created by the subdued "white" luminance and the slight blackening effect of the monitor light interstices) that it is a surface. The printed paper is a true surface, and therefore the inks printed on it have the absorptive grayness (http://www.handprint.com/HP/WCL/color2.html#grayness) that characterizes surface color perception.

If you hold the printed diagram next to your computer monitor and illuminate the paper so that it appears as white as the white of your computer screen, you will see that the inks appear to be darker and less saturated than the monitor colors. So the first difficulty is that absorbing inks are inherently a less effective source of luminance than emitting lights.

If you next look at the printout by itself, you see that the yellow created from the pure **Y** ink (top row) is much brighter than the yellow created from the visual fusion of alternating, printed **R** and **G** dots. Your printer renders the pixels without black space between them, so the darkening is not the same as on your monitor; rather, visual fusion *averages* the luminance (reflectance) of adjacent dots; it does not *add* them together as it does in blended light mixtures. The average lightness of red or green inks is far lower than the lightness of a pure yellow ink, so the visually fused and additively interpreted yellow appears much darker and, therefore, closer to a dull ochre or brown. A similar dulling and darkening occurs in the cyan and magenta mixtures.

Thus, the **RGB** primaries suffer from three handicaps when displayed on surfaces: (1) they lose the greater luminance contrast possible in light sources, and (2) as surface colors, the RGB inks are much darker than pure cyan, yellow or magenta inks. This severely compromises their effectiveness in the additive color mixing induced by visual fusion.

Because RGB inks make drastically darker subtractive mixtures think of mixing yellow from a red and green paint! (3) RGB inks would have to be printed as separate, *nonoverlapping* dots. This would double the visual texture of a printed image and greatly increase the registration (dot alignment) precision necessary for a clear image.

Because subtractive colors can be overprinted in a single dot or pixel location, to produce subtractive mixture with each other and with the white paper, they produce a much finer visual texture with less registration precision. The overprinting also subtractively creates the span of orange, green and violet colors necessary to complete the hue circle. These dots of subtractive mixture are effaced by visual fusion, and averaged together by additive color mixture. This provides an acceptable simulation in printed surfaces and photographic papers of the brightness and contrast experienced in the light images of monitor phosphors, projective transparencies, and the surfaces of the real world.

Substance Uncertainty. In my explanation of additive and subtractive color mixture (), I stated that subtractive color mixture is unpredictable and at best approximate, and that this is because of the complexity of material color mixture.

Now we look at that problem using specific examples. These highlight the differences between the conceptual color, visual color, radiant color and material color as we try to understand material color mixtures.

Visual Color vs. Material Color. To begin, let's clarify the distinction between *material* color, the physical pigment or dye, the *radiant* color the light wavelengths that a paint, dye or ink reflects to our view, and *visual* color, the color of paint, dye or ink we perceive in our experience.

The *material color* the light absorbing and light reflecting attributes of a pigment or dye are exactly described by its spectral reflectance curve (http://www.handprint.com/HP/WCL/color3.html#reflectance) or radiant color. For that reason the guide to watercolor pigments (http://www.handprint.com/HP/WCL/waterfs.html) provides the reflectance curve of all major pigments, linked from the spectrum icon
.

If we are only interested in the appearance of a pigment or dye in isolation, then the radiant color in turn defines the photoreceptor responses under normal viewing conditions, or the material's **visual color**.

So long as we only consider the radiant color only, or the mixture of separate radiant colors that stimulate the eye at the same time (for example, when two beams of filtered light are overlapped on a white surface, or two pigment or ink colors are visually mixed with a color top), then we are in the domain of additive color theory. Predicting these color mixtures using the separate reflectance curves is straightforward and, as perceptual prediction goes, remarkably precise.

But when two or more material colors are *physically mixed* (for example, when a single beam of light is passed through two separate filters, or two pigments are mixed in the same vehicle, or two inks are overprinted on the same substrate), *all* the physical qualities of the substances interact, which can cause their radiant colors to combine in unexpected ways and produce a very unexpected result in the visual color.

The most important of these physical mixture issues are:

38. Visual color cannot identify a unique material color (physical substance) or radiant color (reflectance or transmittance curve).

The same green visual color can be produced by many different material colors and/or radiant colors, a perceptual ambiguity known as material metamerism (http://www.handprint.com/HP/WCL/color6.html#metamerism). Because material color mixtures are highly specific in their effects on radiant color, different material colors can appear to be the same "green color," but will produce different blue colors when each is mixed with the same purple paint. Unfortunately, the paint color appearance (visual color), not the reflectance curve (radiant color), is all that a painter conveniently has to work with.

39. The radiant color (reflectance or transmittance curve) changes with

the physical state of the material color.

A pigment such as quinacridone violet (PV19) does not have fixed radiant color attributes. The reflectance curve, and hence the apparent color under standard viewing conditions, changes with the physical state of the pigment the pigment may be dry or wet, it may be suspended in water or oil, it may be diluted or concentrated, it may be displayed as a thin or thick layer (diagram, right). In most colorants, each of these physical changes will alter the radiant and the colorant's subtractive mixture behavior.

40. The separate radiant colors of pigments cannot specify the visual color of their subtractive mixture.

There are many more physical attributes to a colorant than its reflectance properties. The same reflectance curve can be produced by substances that differ greatly in particle size, refractive index, transparency (hiding power) and tinting strength, and these all can affect how the colorants will appear when dispersed in a vehicle, or which colorant will dominate when used in a mixture with other dyes or pigments.

41. Subtractive mixing behaves differently in different types of material mixtures.

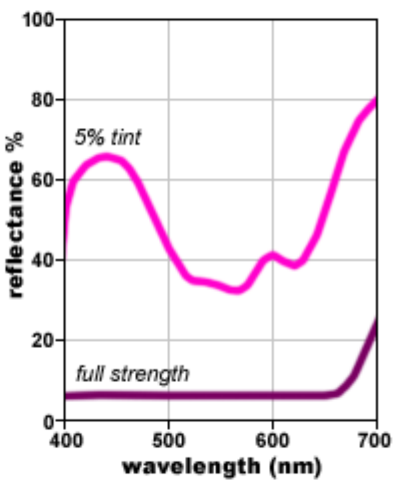
The identical pigments or dyes will create different colored mixtures when mixed in different media. Subtractive mixtures of reflecting paints or dyes obey than subtractive mixtures of transmitting filters; paints applied to highly absorbent white paper appear duller and whiter than paints applied to heavily sized white paper; pigments applied as watercolor (which does not form a paint layer (http://www.handprint.com/HP/WCL/tech16.html#papersurface)) appear different from paints applied as oils or acrylics (which do form a paint layer).

Each of these problems, taken separately, can create formidable problems in describing or "predicting" material color mixtures. In combination, they overcome any generalizations based on visual or conceptual colors.

Even if we do know all the important physical attributes of the colorants we mix, the prediction of their subtractive mixture from their separate reflectance curves is mathematically complex. As a color chemist in the automotive industry explained to me, *you mix the two pigments and look at what you get*. Or as I like to say, subtractive color mixing concepts are only useful as a compass to color improvisation (http://www.handprint.com/HP/WCL/color14.html#mixmethod).

Visual Color Can't Predict Material Mixture. To clarify the extent of these issues, for the moment let's limit the discussion just to material metamerism. This dictates the modern color theory rule that

42. The visual color of a paint does not predict the visual color of mixtures made with the paint.



reflectance curve changes
with physical state

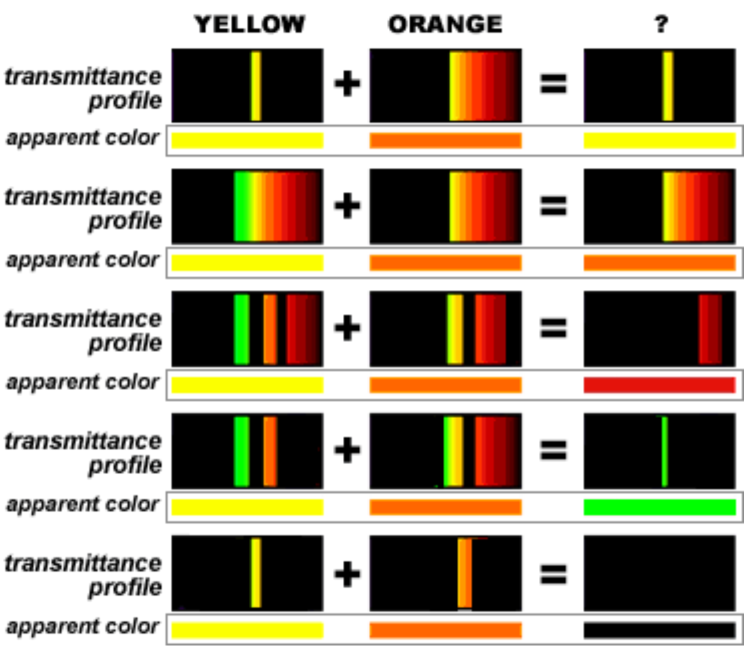
the masstone reflectance curve of quinacridone violet (PV19) changes shape, not just overall level, when it is diluted into a tint

There is a conceptual and a factual way to demonstrate the depth of the metameric problem. Let's start with a conceptual illustration.

Imagine two idealized photographic gel (transparent) filters, designed to pass either 100% or 0% of the light at each wavelength. There are no limits on the combination of specific wavelengths we are able to filter, except that in every case one filter must make a "white" beam of light appear yellow, and the other must make a "white" light appear orange.

We place the two filters in front of a single beam of "white" light. Then the apparent color of the transmitted light is the additive (retinal) mixture of all the wavelengths passed by the subtractive (material) mixture of the separate spectral transmittance profiles.

What color results from this mixture of a visual yellow and a visual orange? As the examples below show, the answer is *it is impossible to say!*



subtractive mixtures of different yellow and orange filters

In the five examples, each pair of ideal filters would appear yellow and orange they would all have the same hue, though they would differ in lightness or chroma. Yet their mixture would produce very different results depending on the specific overlap in their transmittance profiles. Yellow and orange can combine to make yellow, orange, red or black ... yellow and orange filters could even mix to make green!

These conceptual examples demonstrate that there is no logical or necessary connection between the *visual color* of two substances and the color of their subtractive mixture. There can never be universal or invariable color mixing rules in subtractive color mixing they simply don't exist.

Material Color Mixture in Paints. But let's get practical. The extreme, idealized filters I've described are physically implausible. And we certainly can't mix a red color from two gray paints! In fact, very useful regularities or patterns often appear in the way colored substances mix.

Those patterns occur because we live in a real world of atomic substances, and the atomic causes of color (http://www.handprint.com/HP/WCL/color10.html#colorcauses) follow the organizing patterns of chemistry and physics. These tend to produce transmission or reflectance curves in most substances that follow more regular patterns, such as the "warm cliff" (http://www.handprint.com/HP/WCL/color12.html#cliff) profile typical of saturated red, orange and yellow paints and filters. In addition, painters work with a very limited range of colored substances chemically pure and complex colorants, the pigments in their paints and modern colorants create a fairly predictable domain of reflectance profiles.

So we have to turn to *paint* color mixtures to evaluate the practical impact of the metameric problem *for painters* (or anyone else mixing paints, dyes or inks).

To do that, let's see what happens with the most explicit paint mixing test possible (and the one most beloved in traditional color theory): making a *pure gray mixture* from two complementary paint colors (http://www.handprint.com/HP/WCL /color13.html#compprobs).

The test is simple (though tedious) to do. The results I will show you here are described in detail on this page (http://www.handprint.com/HP/WCL /mixtable.html), but the logic behind the test is easy to understand.

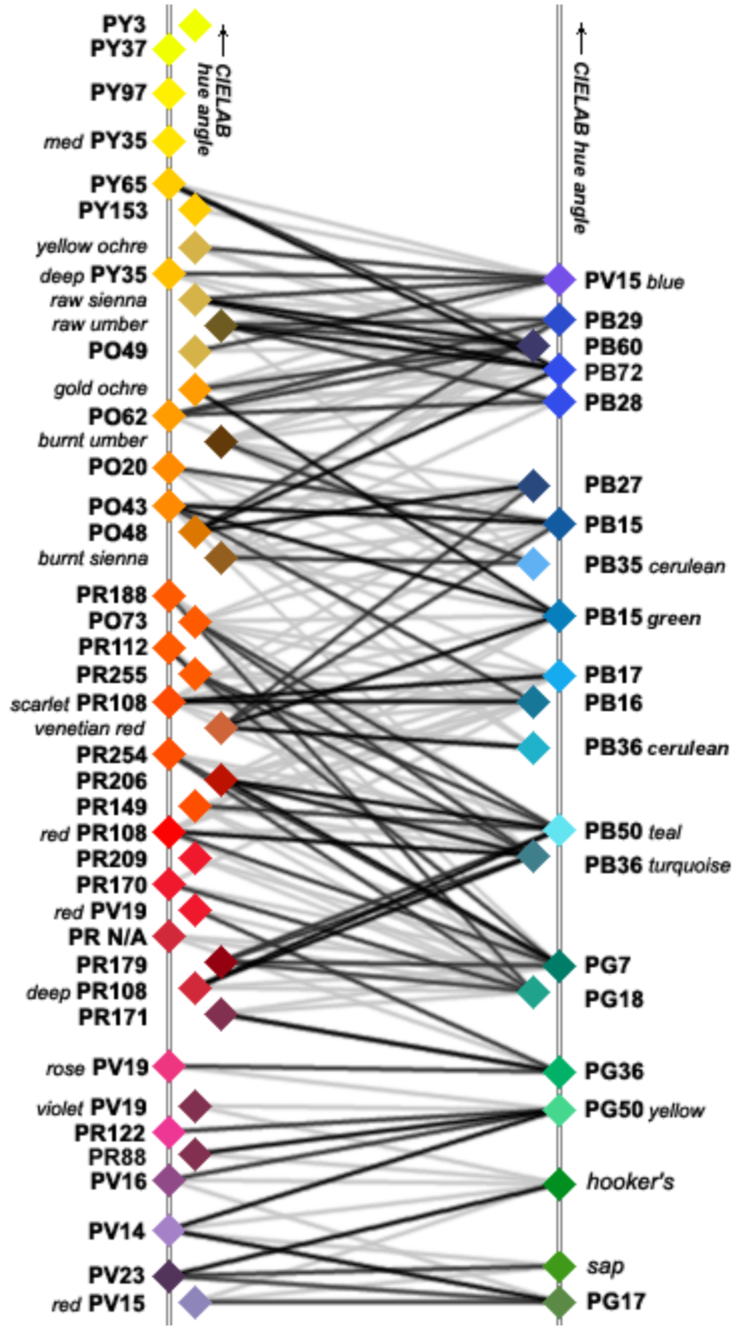
First, using the visual color only, arrange all the available "warm" colored paints in a series, from green yellow to violet, on one side of a page. Then arrange all the complementary "cool" colored paints, from blue violet to yellow green, on the opposite side. Align the paints up or down on each side until the mixing complement pairs (http://www.handprint.com/HP/WCL/mixtable.html) are directly across from each other violet blue across from yellow, blue across from deep yellow, green blue across from orange, and so on.

Then mix *all possible combinations* of a warm paint with a cool paint, and identify by eye the paint pairs that actually produce a neutral (gray or black) mixture.

Finally, connect these visually verified mixing complement paints with a dark line.

Now, if complementary paint mixtures are exactly determined by the *visual color* of the paints, and if all the paints have regular, simple reflectance curves, then lines connecting these complementary pairs should be roughly parallel (diagram, right). As the hue of the warm paint changes from deep yellow to violet, the hue of its mixing complement should change from blue violet to green by an equal amount.

This is precisely what *does not* happen, as shown below.



substance uncertainty in watercolor material mixtures

mixing complementary colors as measured on the **a*b*** plane in CIELAB: pigments that make "pure gray" mixtures are joined by dark lines, "near gray" mixtures by light lines (see this page (http://www.handprint.com/HP/WCL/tech17.html#mixing) for more information)

The mixing lines from each pigment fan apart, or skew up or down haphazardly.

And this is not just because there is a greater number of pigments on the warm side, or the warm pigment hues are more similar. Consider the examples (diagram, below) where two pigments with very different visual colors make a perfectly gray mixture with a third paint color. (The two examples at far right show that two visually different pigments can have the same mixing complements.)

visual color variety among material color complements

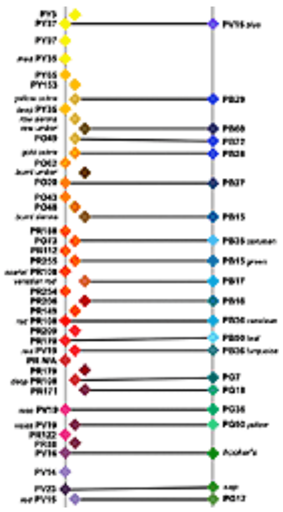
the same pigment (top row) mixes a pure gray with either of the two pigments enclosed by the box (bottom two rows); diagram matches the pigment color appearance as measured in the CIELAB color space with a spectrophotometer

This demonstration clearly shows why a mixing color wheel (http://www.handprint.com/HP/WCL/color16.html#mixprobs), which arranges paints around the hue circle according to their complementary mixtures, can never accurately define the mixing behavior of pigments or paints. If we align cobalt teal (PG50 (http://www.handprint.com/HP/WCL/waterg.html#PG50)) directly opposite its mixing complement pyrrole orange (PO73 (http://www.handprint.com/HP/WCL/watero.html#PO73)), then it will not be opposite its other mixing complement, perylene maroon (PR179 (http://www.handprint.com/HP/WCL/waterr.html#PR179)). If we place cobalt teal at some average position, opposite the middle hue between pyrrole orange and perylene maroon, then we would have to place viridian (PG18 (http://www.handprint.com/HP/WCL/waterg.html#PG18)) in exactly the same position, because it has exactly the same mixing complements!

The diagram also shows the limitations of using conceptual colors, such as the traditional color theory "primary" colors, to explain color mixing. For example, cobalt teal blue (PG50 (http://www.handprint.com/HP/WCL/waterg.html#PG50)) mixes a pure gray with both pyrrole orange (PO73 (http://www.handprint.com/HP/WCL/watero.html#PO73)) and cadmium red deep (PR108 (http://www.handprint.com/HP/WCL/waterr.html#PR108)). But pyrrole orange has a distinctly yellow component in its hue, and therefore has substantially more "yellow primary" in it than cadmium deep red. So then how can a paint with more "yellow primary" in it mix the same gray with the same green blue paint? The conceptual "primary" colors have no logical or necessary connection to the visual color of two material colors, or to the color of their physical mixture.

The limiting rules of physics and pigment chemistry do take us out of those idealized transmission filter examples, where subtractive color theory doesn't exist at all. But they don't take us all the way to a perfect world where pigments with the same visual color mix in a consistent way. We end up somewhere in the middle in a fuzzy, messy real world where subtractive color mixing is a real fuzzy mess.

Other Factors in Material Mixtures. Couldn't we avoid substance uncertainty if we were somehow able to use only colorants that had regular and simple reflectance curves? The answer is no: because the substance uncertainty arises from the many invisible differences in pigment *material attributes* refractive index, particle size, crystal form, hiding power and tinting strength. Thus, the pigments cadmium yellow medium (PY35 (http://www.handprint.com/HP/WCL/watery.html#PY35)) and hansa yellow medium (PY97 (http://www.handprint.com/HP/WCL/watery.html#PY97)) have almost identical *reflectance curves*, yet they produce visibly different mixtures with other paints because their refractive indices (http://www.handprint.com/HP/WCL/pigmt3.html#refractiveindex) (appearance in paint vehicle) are so different.



idealized subtractive mixing complements in watercolor paint mixtures

What if we could somehow make paints so that every apparent color had the same reflectance curve, and made sure every paint had exactly the same material attributes wouldn't that solve the problem? Again, the answer is no: because *all* the material attributes of the mixture are involved, and that includes the material attributes of the support and the paint application methods.

The qualities of different paper or canvas supports have a significant impact. A glossy, highly reflective white paper can show up to 24,000 distinct color mixtures using modern CYM process inks. The same inks, printed on ordinary newsprint, generate a much smaller range of perhaps only 2,000 distinct colors and these are all significantly duller and darker. In watercolors, a highly absorbent paper (which pulls the pigment particles between the cellulose fibers) will produce lighter, duller color mixtures than a heavily sized, hot pressed, nonabsorbent paper. Applying paints to paper effectively mixes *three* light reflecting substances the two paints in the mixture and the paper so the material attributes of all three will determine the apparent color.

Color mixtures also depend on how the paints are applied. A familiar example for watercolorists occurs when paints are mixed by glazing or layering one color over another: cadmium yellow over phthalo green is a lighter and less saturated mixture than phthalo green glazed over cadmium yellow, even though we have put the same paints, in the same quantities, on the same paper.

These complications of material metamerism, physical attributes, support attributes and application methods all contribute to the same modern color theory principle: **visual color does not predict material mixture color**. Subtractive color mixing "theory," by trying to imitate additive color mixing theory, bites off much more than it can chew.

The Color Is In the Mixture. Substance uncertainty is such a difficult problem that traditional color theory deals with it the only way it can by *ignoring it!* Or, even worse, by *denying it* and organizing color mixtures within idealized triangles or circles.

The artist tries to mix paints according to these idealized, perfect color theory rules is guided to some degree, but is often also confused by the many mixture exceptions that result. Painters who learn color theory in terms of the *visual* colors of paints arranged on a color wheel (http://www.handprint.com/HP/WCL/color13.html) learn how to mix *conceptual hues* "yellow and blue make green" rather than *paints*.

If visual color really is separate from material color, how can we manage color as basic principles? Which form of color should we think about? For now, we seem to have another modern color theory rule:

43. The material color of a paint is defined by the visual colors it makes in mixtures with all other paints.

But this raises the problem: how do we define the conceptual color of a paint? If two "blue" paints mix differently, or a teal and blue green paint mix similarly, then we need to have a color space, or a color language, that can express those differences.

To create this kind of conceptual color language, we must examine the *color relationships* that have, in traditional color theory, been expressed as simple geometries of circle or triangle. And we must learn the concepts of a *colorant gamut* that help us visualize the behavior of specific paints.

visual color relationships

The previous two sections have used additive and subtractive color mixing, and the problems of substance uncertainty, to illustrate the differences among conceptual, visual and material color.

Now we turn to the issue of color relationships in general, or how the artist can best "think about" color.

It will be clear that the appropriate form of color to use in this area is the visual color. Material color is too unreliable, or too variable, to serve as a basic framework for color relationships, and conceptual color represents ideas that must be developed out of experience.

44. Visual color, the domain of color experience, is the foundation for all conceptual color relationships.

The Concepts of Illuminance & Luminance. The fundamental visual color relationship is produced by the appearance of colors under different levels of illuminance or luminance, two concepts that all artists and photographers should understand clearly. Their effects on visual color are profound.

The diagram (right) shows the relative relationship between benchmark illuminance and luminance values across the range of common light environments (http://www.handprint.com/HP/WCL/color4.html#sensitivity). The chart is designed so that an illuminance level is directly across from the luminance it would create on a white surface.

Illuminance (http://www.handprint.com/HP/WCL/color3.html#illuminance) is the *quantity of light incident on (falling on) a surface area*. In most environments there are many different surfaces in view, and they all receive different amounts of light; the average illuminance across all surfaces that are not in shadow is the **light environment**.

Illuminance depends on distance. *Illuminance decreases by the inverse square of distance* if you are 2 times farther from a light then its illuminance decreases to 1 divided by 2 squared, or 1/4; or, if you reduce the distance to a light by 1/2, you increase its illuminance by 1 divided by 1/4, or 4 times (the *inverse square law*). Using the chart at right, we can calculate that a single wax candle at 32 meters provides the same illuminance as a starry night sky.

Paradoxically, *illuminance is always invisible:* we cannot, by eye alone, judge illuminance in any light environment. Instead we judge it indirectly, through the *luminance* that appears in the light reflected from objects and surfaces.

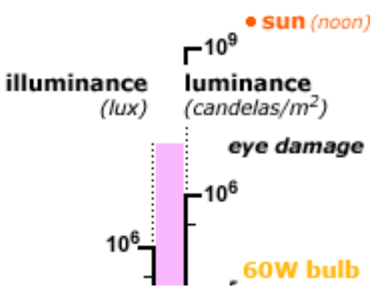
Luminance (http://www.handprint.com/HP/WCL/color3.html#luminance) is the *illuminance received from a light source averaged across its visual area*.

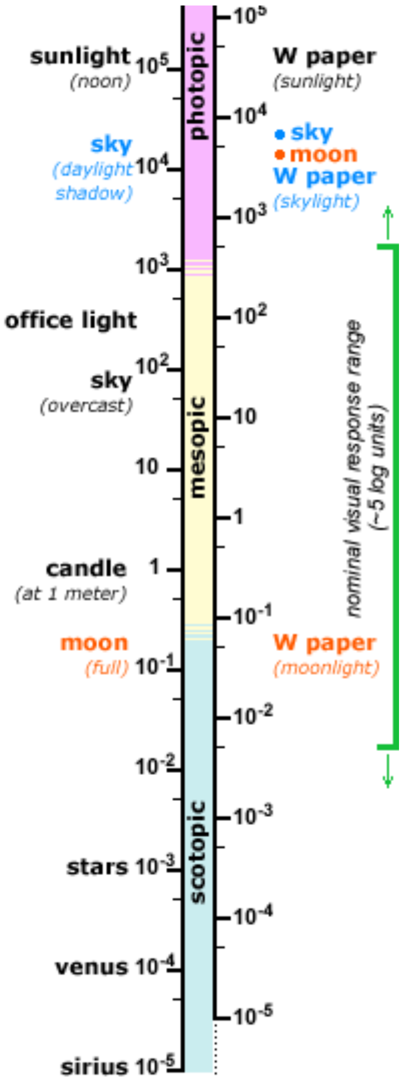
Luminance depends on physical size of the light source, not its distance from us. If two light sources provide the same illuminance at the same distance, the physically smaller source will appear more luminous (brighter). If we move away from a light source, the visual size of the source decreases in the same inverse square proportion as the illuminance received from it, so the luminance remains constant.

The diagram (right) illustrates the relationship between apparent size, luminance and illuminance. But the luminance of the source of the illuminance depends on its size. Because the moon is visually small, it appears much brighter than a sheet of white paper it illuminates. Because the sky is visually very large, it is only as luminous as the paper it illuminates. This is the rationale for large diffusing light panels in modern office spaces: they provide lots of light without the apparent brightness that can cause eyestrain.

The amount of light that can affect a receptor surface depends on the surface area receiving the light, or the area of its opening to light (*aperture*). Contraction in the size of our pupils makes lights appear less bright, and closing the diaphragm in a camera increases the exposure time of the film; the brightness of lights we see depends in part on the diameter of our pupil.

Across different adaptation levels (day vs. night) and illuminance regimes (a room interior in shadow and, through a window, a landscape exterior viewed in daylight), the human eye can accurately report luminance differences within a relatively constant luminance range of about 5 log units, or a ratio of 1:100,000 (diagram, right). This is its contrast ratio (http://www.handprint.com/HP/WCL/color4.html#charcurve). Luminances outside this range appear either as black or undifferentiated dark areas, or as glaringly bright lights.





a comparison of common light environments (log scales)

at 1 lux = 0.31 candela/m^2, the luminance of a white sheet of paper matches the illuminance falling on the paper

All photographic and painting media have similar but much smaller *luminance* contrast ratios, generally in the range of 1:100. (*Media* contrast ratios, such as dye pigment densities or monitor light steps, are often larger than the visible contrast ratio.) If we want to include the stars in our image, then we cannot accurately render anything much brighter than the moon in the same image. If our brightest white is white surface in sunlight, then our blacks are actually brighter than a white surface under office lights (image, right).

The process of rendering the visual range of luminance and chromaticity values within the smaller contrast range of material (photographic, painting and digital) colorants is called **gamut mapping** or **tone mapping**, a procedure explained in the page on tonal value (http://www.handprint.com/HP/WCL/color11.html#paintzone).

Visual Color & Luminance Adaptation. As illuminance goes up or down, the luminance of the surfaces goes up or down in exact proportion. The eye adjusts its sensitivity so that the visual response range brackets the average value of surface luminances: this is luminance adaptation (http://www.handprint.com/HP/WCL/color4.html#sensitivity). To sustain this adaptation range, we avoid looking directly at luminous light sources.

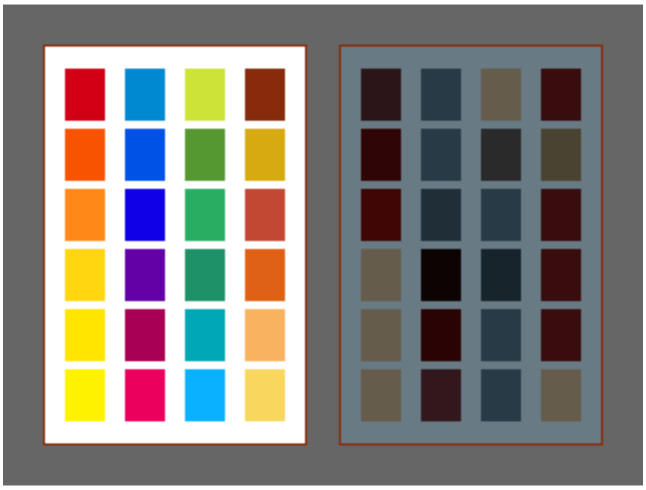
Visual color changes substantially across different levels of luminance adaptation. The three basic adaptation regimes are:

photopic (above ~1000 lux) - color perception is present and lightness, hue and chroma contrast are at their peak; contrast is enhanced in darker values, and the chromaticity of light sources is obscured by their brightness.

mesopic (~0.1 to ~1000 lux) - color perception is present, but lightness and chroma contrast are reduced, especially in darker colors and at lower light levels, hue contrast is reduced in greens and blues; the chromaticity of light sources is accented by their dimness.

scotopic (below ~0.1 lux) - color perception is absent, and replaced by gradations of lightness only; lightness contrast is greatly reduced, and disappears across darker values; edge contrast and object details are significantly obscured.

The transition from mesopic to scotopic (light to dark) illuminance levels produces complex and rapidly changing color effects, described in detail on this page (http://www.handprint.com/HP/WCL/color4.html#scotopiccolor).



change in visual color from mesopic to scotopic vision

(left) color samples viewed under ~200 lux; (right) color samples viewed under ~0.2 lux, just before color perception is lost

The diagram (above) shows the visual color of 24 watercolor paints viewed under sky illuminances at sunset and 45 minutes after sunset, just before the transition to scotopic vision is complete. The full range of colors has degenerated to a limited range of warm and cool hues, very poorly separated in lightness.

45. Illuminance is manifest *inside* color experience, as a qualitative color attribute or "color consistency".

Color experience does not report a white surface under moonlight as merely a visual gray that would be matched by a material gray surface viewed under mesopic illumination. The appearance of the "gray" itself is qualitatively different, so that we *see* the illuminance level, or our luminance adaptation, in the color experience. This is perhaps the most remote and subtle aspect of color than an artist can observe and attempt to render in an image.

Visual Color & Illuminance Contrast. We judge colors under the assumption that all surfaces in view are under the same illuminance, and that shadows all form in the same direction, away from the dominant light source.

If the spatial relations that create illuminance differences are obscured, then our visual color judgments suffer. Color lightness contrast, apparent white/gray value, chroma and even hue can be badly distorted.

Isaac Newton (http://www.handprint.com/HP/WCL/color2.html#whitepigments) recognized the importance of illuminance contrast to visual color over three centuries ago, when he studied luminance dependence in white and gray:

luminance rendering within a 1:25 (~5 photographic stops) imaging contrast ratio

Considering that these gray and dun Colours may also be produced by mixing Whites and Blacks, and by consequence differ from perfect Whites, not in Species of Colours, but only in degree of Luminousness, it is manifest that there is nothing more requisite to make them perfectly white than to increase their Light sufficiently. ... And this I tried as follows. I rubbed [a mixture of blue, green, yellow and red pigments] *thickly upon the Floor of my Chamber, where the Sun shone upon it through the opened Casement; and by it, in the shadow, I laid a Piece of white Paper of the same Bigness. Then going from them a distance of 12 or 18 Feet, ... the Powder appeared intensely white, so as to transcend even the Paper itself in Whiteness. Opticks* (1704), Book I, Part II, Experiment 15.

The images (right) show the same material color (a red iron oxide or "burnt sienna" paint), displayed either as a sunlit area within a shadowed surround, or a shadowed area within a sunlit surround. Illuminance contrast (variations in the radiant color) can make the same material color appear orange, brown or black.

46. Luminance contrast produced by illuminance contrast produces a local increase in both lightness contrast and chromaticity contrast, with minimal effects on hue.

I have experienced illusory luminance contrast rarely: once when I looked out my bedroom window an early morning to survey the building site of my studio. I was surprised to see an unfamiliar, large brilliant orange box sitting in a sloping field nearby, profiled against a background of dark trees. Only after repeated looking did I realize it was actually the contractor's *dark brown* safe box, illuminated by a nearly horizontal shaft of sunlight piercing through trees behind my house.

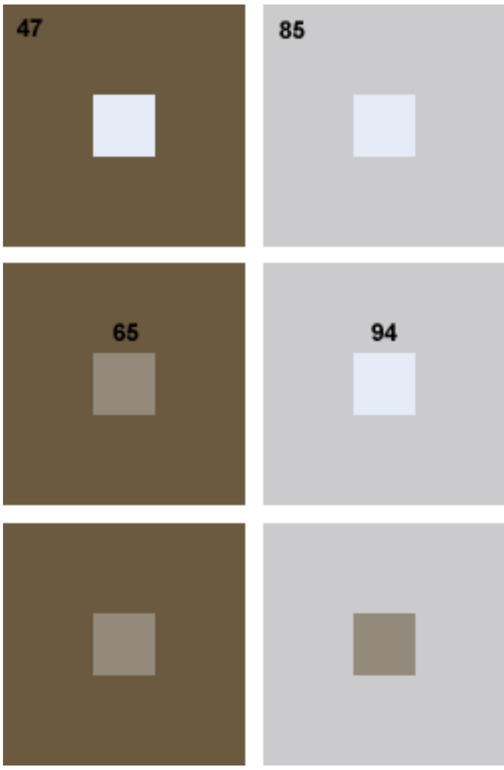
Well, not so rarely ... less reputable art galleries simulate chromaticity contrast when they illuminate paintings hung on a dimly lit wall by means of spotlights with very diffuse boundaries. Because the illuminance boundary is not visible, the illuminance contrast causes the paint colors to appear more saturated and more contrasted than they will appear when both the painting and the wall are viewed under the same light source.

Visual Color & Spatial Factors. We are typically adept at reconciling the infinite possible permutations of illuminance contrast within light environments in terms of the spatial configuration of surfaces.

Traditional color theory has almost entirely ignored spatial effects in visual color the studies of by Joseph Albers (http://www.handprint.com/HP/WCL

/book3.html#albers) being one of the notable exceptions but these effects are incredibly large. We can suggest this impact through parallel color contrast examples.

First consider the traditional color theory presentation of squares within squares, the favorite device to demonstrate the demonstrated at length by Michel-Eugène Chevreul (diagram, below).



simultaneous color contrast

two different central colors, contrasted in the middle row, against two different background colors, contrasted in the two vertical columns; a single central color appears in the top and bottom rows; lightness (**L***) values included

Here we see the traditional simultaneous contrast effects in both the top and bottom rows: the dark central color appears darker on a light surround, and the light central color appears lighter on a dark surround. On this evidence, vision seems designed primarily to make different colored areas appear as different as possible, and the induced shift in the light and dark areas appears about equal.

spatial color contrast

a sheet of white paper viewed in direct illumination and partial shadow (middle row) original photograph; (top row) illuminated paper copied into shadowed area; (bottom row) shadowed paper copied into illuminated area;

When the same average color contrasts are placed in a spatial context, they present a different and much greater impact. The agnostic lightness difference between the two background colors in the previous figure is now a three dimensional illuminance contrast on the same spatial surface, which requires us to interpret the color area contrast the contrast between the two sheets of paper in a spatially consistent way. Two effects appear:

increased contrast - the comparative impact of the color differences is drastically increased: we perceive a much greater difference between the illuminated and shadowed surfaces than in the simultaneous contrast demonstration.

nonlinear contrast - the contrast produced by copying the shadowed area into light is much greater than that produced by copying the lighted area into shadow: the same visual contrast has a much greater "blackness" impact. The ratio of the lightness contrast is the same, but in the bottom row the color is both lighter and darker than the background.

These enormous visual differences signify that color is not merely a medium through which we can see the qualities of *light absorbing materials,* but a medium through which we see the reality of *light in three dimensional space*.

47. Vision primarily and preferentially interprets surface luminances (reflectance) in terms of the spatial distribution of light in a three dimensional environment.

We do not have to strain our imaginations to see a building in a photograph or a face in a painting

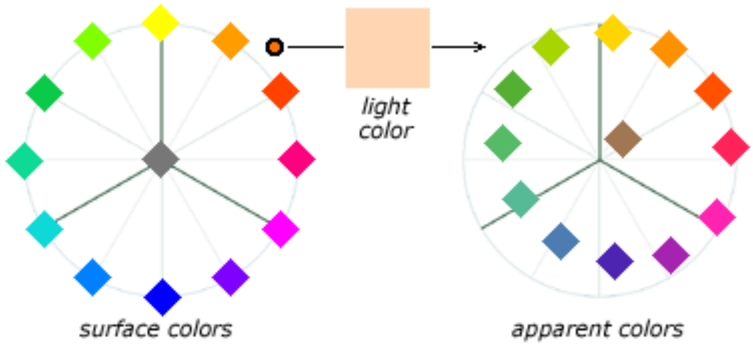
Illuminant & Visual Color. The spectral composition of a light source (summarized as an illuminant (http://www.handprint.com/HP/WCL/color1.html#dayphases)) determines its chromaticity, and this has a significant effect on color appearance.

In most natural light environments, *daylight* (the combination of sunlight and skylight) is quite variable across the time of day and type of weather. However these changes in daylight spectra follow a consistent chromaticity path (http://www.handprint.com/HP/WCL/color12.html#daylocus) from a slightly blue to strongly yellow chromaticity. These chromaticity changes can be indexed as the correlated color temperature (http://www.handprint.com/HP/WCL/color12.html#CCT) of the light. Noon daylight has a CCT of about 6500, while sunlight at sunset has a CCT of around 2000. CCTs can also be used to describe artificial light sources; most incandescent lights have a CCT below 3000, which is rather yellow.

Our visual system is adapted to eliminate the effects of moderate chromaticity in lights, especially across daylight spectra, through a process of chromatic adaptation (http://www.handprint.com/HP/WCL/color4.html#chromaadapt). This is provided the lights contribute to the light environment, as is most apparent at night. When we are indoors after sunset, the illumination from incandescent lights, or a television screen in a dark room, will appear "white"; but if we view these lights from outdoors, as the light falls on a white sheet or window shade, the same illumination will appear distinctly yellow or blue.

In more extreme cases, such as the illumination from a heat lamp or "black" light (ultraviolet light), the chromaticity of the light cannot be eliminated by chromatic adaptation. However we may still be able to judge visual color accurately, as if we saw normally illuminated colors through tinted glasses.

All surface colors are altered by the chromaticity of the illumination. This alteration is effectively a subtractive mixture of the chromaticity of the light with the chromaticity of surface colors. Surface hues close to the hue of the light increase in apparent chroma and appear more similar; hues opposite are grayed or muted; hues perpendicular to the light hue are hue shifted toward the light.



effect of an orange light source on surface colors

analogous surface hues and grays are made more chromatic and more similar to the light hue; complementary surface hues are made less chromatic

As with the that occurs in the subtractive mixture of two substances, we cannot predict the visual color of surfaces from the visual color of the light source. Low pressure sodium lamps appear yellow, but make both reds and greens appear achromatic. Some fluorescent lamps appear white, but have a concentrated spike of luminance in "green" wavelengths that makes green colors appear unusually saturated or "fresh" (a fact utilized in the lighting of many supermarket produce displays).

Lights can be rated on their color rendering (http://www.handprint.com/HP/WCL/color12.html#colorrendering) properties: incandescent (tungsten or halogen) lights typically match the perfect color rendering properties of noon daylight.

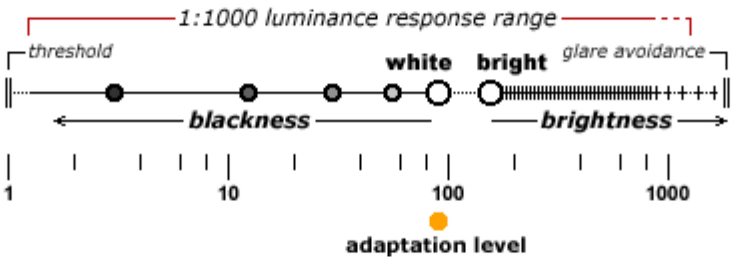
Luminance & Achromatic Values. My emphasis on the powerful effect of the light environment and color luminance on visual color leads naturally to the most important dimension of color relationship discussed in traditional color theory: *value,* or the colormaking attribute of .

Variations in lightness provide almost all the structure in an image: this lightness dominance (http://www.handprint.com/HP/WCL/color11.html#dominance) is apparent if we remove either the chromaticity contrast or the lightness contrast from an image, and compare the revised versions to the original (images, below).

the dominance of lightness contrast

a painting by Winslow Homer in its original form (top), then as lightness contrast with no chromaticity contrast (left) or as chromaticity contrast with no lightness contrast (right)

The diagram below shows our visual response within a luminance range of 1:1000, a conservative estimate of the human contrast ratio. (The contrast ratio is larger in dimmer light environments, but is difficult to measure at the high end due to glare avoidance and the adaptation effect of bright lights.) However, the contrast ratio of surface luminances is more often around 1:20 between perceptual white and black, because most "white" surfaces are materially somewhat gray, and no "black" surface absorbs all light.



luminance contrast, lightness and brightness

log luminance scale relative to dark threshhold = 1, with an arbitrary 1:1000 luminance contrast ratio

illuminance contrasts
and visual color

the same dull orange paint, viewed under higher illuminance, equal illuminance, or lower illuminance than the "white" surround

As shown in the diagram, lightness is a misnomer, since the characteristic of all surface colors is that they contain a component of **blackness** (grayness) they appear to absorb some portion of the light available in the light environment. Lights appear to contain some component of **brightness** rather than blackness (lights can appear dimmer, but not grayer), so blackness and brightness form opposing dimensions of a single luminance scale, with "white" near the neutral or middle point.

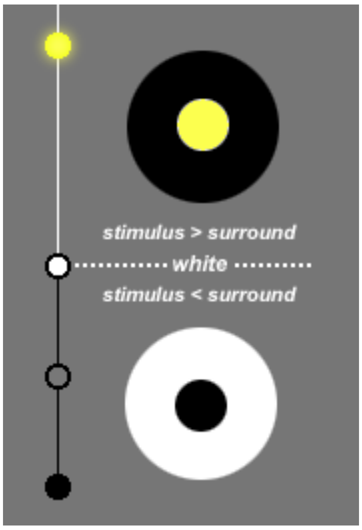
This is the reason why our visual contrast ratio vastly outstrips the contrast ratio possible in all physical media: **luminance is perceptually mapped into two separate visual codes**, which ambiguously join around the luminance of a pure white to "brilliant" white surface.

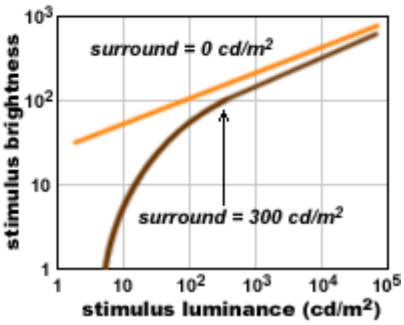
The difference between lightness and brightness is produced by **luminance contrast**. As a simple demonstration, a diffusing light can be presented within either a completely dark surround or a surround at a constant luminance of 300 cd/m^2 (diagram, right top). In darkness, the light appears as "bright" (emitting light) whether its luminance is 10 or 100,000 cd/m^2; but when viewed in the luminous surround, the light begins to darken, and appear as a gray surface, as soon as its luminance is less than the surround luminance (diagram, right bottom). Thus, the "blackness" we see in surface colors is actually a *brightness suppressing response* in our visual system that is stimulated by luminance contrast.

The **adaptation level** can be thought of as the luminance that would produce no change in luminance adaptation if that luminance homogeneously filled the visual field. This is usually said to be a middle gray, or an average reflectance that is about 20% of white the surface commonly used by photographers to estimate photographic exposures.

For the human visual system, adaptation is actually closer to white. This appears in the phenomenon of lightness anchoring (http://www.handprint.com /HP/WCL/color4.html#anchoring), which shifts achromatic perception (http://www.handprint.com/HP/WCL/color4.html#lightdome) so that the lightest valued achromatic surface in view appears as "white", even when it is a middle gray or black (as nicely demonstrated in the Gelb staircase (http://www.handprint.com/HP/WCL/color4.html#gelbstaircase) effect). Thus, after the adaptation response had stabilized, a middle gray color that completely filled the visual field would appear as white.

In addition, this adaptation "white" produces a visual response near the middle (http://www.handprint.com/HP/WCL/color4.html#stepcurves) of the luminance response range when luminance is very high (noon daylight). As a result, we experience the maximum lightness contrast and the greatest discimination in small lightness variations, especially in darker values. The adaptation response shifts toward the bottom end of the response range in dim light or darkness, reducing lightness discrimination among light values and making all dark values from middle gray to black indistinguishable.





lightness induction

from Wyszecki & Stiles (1982)

Despite these dynamic adaptation and anchoring effects, a "white" surface has a qualitatively different appearance in dim or bright light environments changing from a blazing, creamy white appearance in sunlight to a silvery, silky blue gray in moonlight (transitions suggested by the images, right).

Luminance perception is thus a very complex color experience, in which our eye and mind adapt to the light environment, anchor "white" in the lightest valued achromatic surfaces, compensate for illuminance differences (cast shadows and spot lights) within the light environment, and present the adaptation level in color experience as changes in the amount of lightness contrast between black and white and in the qualitative appearance of white as grayed or brilliant.

Painters must wrestle with and consolidate all these effects as they try to render the spectacular color experience of a natural light environment as the color contrasts possible within a physical medium.

The Artists' Gray Scale. Artists are universally taught to interpret and think of lightness variations in terms of a **gray scale** or *value scale,* which breaks down the maximum lightness discrimination of approximately 50 perceptible differences (http://www.handprint.com/HP/WCL/color2.html#graysteps) into a dozen or fewer categories of lightness contrast. The nine step scheme devised by Denman Ross a century ago is still visually handy and easy to remember; it can also be conveniently collapsed into a five step scale (table, below). (Note that *high light* is the value step closest to white, while *highlight* is the image of a light source reflected from a shiny surface.)

denman value scale *valuesamplenamevaluesamplename* **1** white**1** white **2** high light

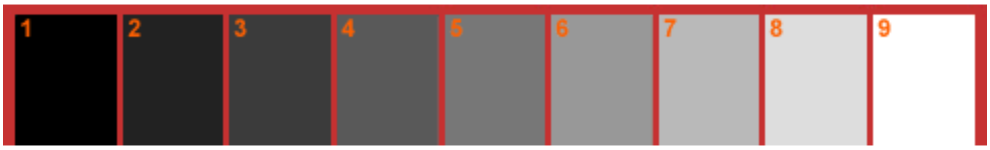
3 light**2** light **4** low light **5 mid value3 mid value 6** high dark **7** dark**4** dark **8** low dark **9** black**5** black

Because value is the dominant element of visual information, it is the most important attribute to consider in visual design. Artists commonly prepare a value sketch (http://www.handprint.com/HP/WCL/tech12.html) of a painting or design, often utilizing only a "black", "gray" and "white" value palette. (See also my Handprint lightness categories (http://www.handprint.com/HP/WCL/color13.html#lightnesscategories).)

The standard in color models (http://www.handprint.com/HP/WCL/color7.html), for example in the Munsell color order system (http://www.handprint.com/HP/WCL/color7.html#munsell), is an 11 step value scale ranging from 0 (black) to 10 (white). The CIELAB L* dimension (http://www.handprint.com/HP/WCL/color7.html#LAB1) is a multiple of 10 of the Munsell scale: a 6 on the Munsell value scale corresponds to a 60 on the L* dimension.

luminance dependent changes in "white" appearance

Artists often use a physical gray scale to visually match the lightness of objects they are painting or drawing. A typical example is presented below. Open the scale image in a new window by clicking on the link below it, print the image on a good quality color printer (with print options set to "black ink only"), and you have a serviceable value scale for use in the field or studio. Preprinted value scales are available from online art retailers, and the standard **photographer's grayscale** (manufactured by Kodak) is sold at most camera stores though the photographer's scale crunches up the range of light values and spreads out the darks.



9 step value scale

Click here (http://www.handprint.com/HP/WCL/val09.html) to view the full size image on gray background

Lightness interval scales such as these are calibrated to differences in perceived lightness between black and white so that each value step appears to be equally different from the steps above and below it. This disguises the fact that lightness is equal to a power of the reflectance (http://www.handprint.com /HP/WCL/color2.html#responsecompression), proportional to the luminance scaled with an exponent of 0.43. These power scales produce finer gradations of value *in dark values,* and more closely match the logarithmic scaling of light energy relevant to film exposure.

Artists use these value scales by holding the scale so that it visually overlaps an area in the field of view, then finding the lightness match between the object and the scale; this is the value that should be matched in the painting. This assumes that only surfaces under the same illumination not surfaces under strongly contrasted illumination, or actual lights are included in the image.

The important exception to rendering illuminance contrast in a painting is the visual color contrast between illuminated and shadowed surfaces. Here the gray scale can be used to calculate the paint value contrast. In bright daylight the contrast between light and shadow creates up to a 60% reduction in lightness, so a sunlit surface matched by a value of 8 will appear as a value slightly above 3 (8 * 0.4 = **3.2**) in shadow.

Shadow contrast may only amount to a 40% or less lightness reduction under overcast skies or indirect (window illuminated indoor) light: then 8 * 0.6 = **4.8** or 8 * 0.7 = **5.6**.

These value contrasts must be reproduced in paint mixtures that maintain the same color saturation between light and dark surfaces (that is, shadows reduce the relative lightness by 60% *and* reduce the color chroma by 60%). If the lightness is reduced more than the chroma, the shadowed surface will appear to be illuminated by a secondary light source. If the chroma is reduced more than the lightness, the surface will appear grayed or blackened rather than shadowed.

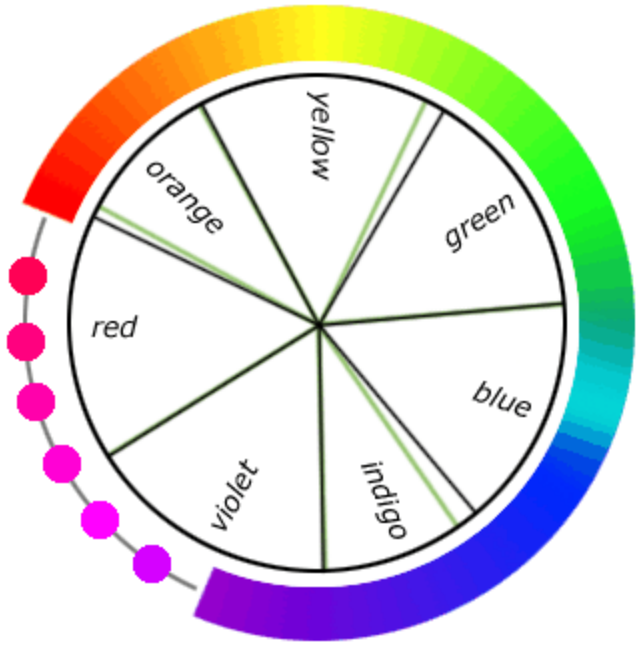
Hue Relationships. Despite the overriding importance of luminance and luminance contrast in color experience, traditional color theory has maintained a long and incredibly disproportionate infatuation with chromaticity especially, with the relationships among and .

Moses Harris (in around 1760) was the first author after Newton to emphasize complementary color relationships, and the first to identify complementary color (http://www.handprint.com/HP/WCL/color4.html#complementary) contrast as an important factor in visual design:

"If a contrast is wanting to any colour or teint, look for the colour or teint in the system [wheel], *and directly opposite you will find the contrast wanted. Suppose it is required what colour is most opposite, or contrary in hue to red, look directly opposite to that*

colour in the system and it will be found to be green, the most contrary to blue is orange, and opposite to yellow is purple."

Hues in Traditional Color Theory. We can trace this infatuation back to the circular arrangement of spectral hues (the color stimuli physically possible) innovated by the English physicist Isaac Newton in 1704. This is the foundation image both for artists' color wheels and for the hue circle in all scientific .



isaac newton's "diatonic" hue circle

from *Opticks* (1704), Book I, Proposition VI, Problem ii. Newton's division of the hue circle as a diagram (black lines), and as 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

Newton's hue circle exemplifies three ruling issues in traditional color theory, which it will be enlightening to put in context. The issures were:

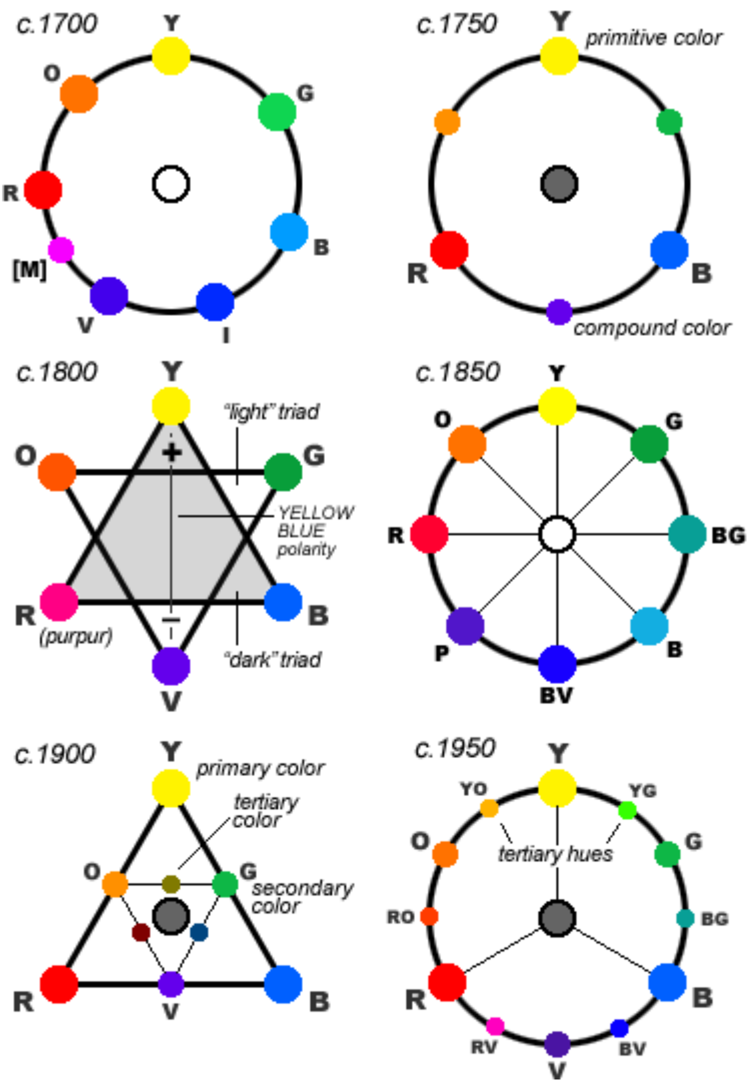
simple geometry. Newton apportioned the hue circle into seven hues red, orange, yellow, green, blue, indigo and violet and spaced them by analogy to the whole number fractions (http://www.handprint.com/HP/WCL/tech13.html#newton) used to describe a diatonic musical scale in a vibrating string (the C major scale starts at violet, and orange and indigo represent half tone steps). This abstract geometry was based on the observed or *visual color* sequence and spacing of spectral hues.

measurable mixtures. Newton chose a circular geometry in order to explain measurable light mixtures (http://www.handprint.com/HP/WCL/color2.html#mixingcircle), specifically the fact that specific quantities of red, yellow, green and blue colors of light produced an achromatic or "white" mixture, represented by the center of the circle. These relationships therefore describe *additive* mixtures of light.

primary colors. Newton complicated the idea of "primary" colors, first calling *all seven* colors of light equally "primitive" and irreducible, then dismissing them all as sensations in the mind. Naturalists and painters who adopted Newton's circular geometry and measurable mixture relationships wanted to explain material color mixtures in pigments, and therefore inserted the painter's three primary colors into the hue circle. This made it appear that a hue circle can describe *subtractive* color mixtures, and made it appear that material color and radiant color were the same thing.

These three issues (and several others), in the context of both scientific and artistic uses of color, made Newton's scheme appear arbitrary or inconsistent (http://www.handprint.com/HP/WCL/color6.html#confusions) to many 18th and 19th century readers. In addition, mixtures of light had no practical application, and were much more difficult to measure or manipulate than mixtures of pigments (paints or inks) and dyes.

So Newton's hue circle was revised toward more traditional and practical concepts, useful to printers and painters. But quite a lot of uncertainty remained in the way colors would be represented, as suggested by a sampling of historical hue models (diagram, below).



color theory color icons

c.1700: additive hue circle after Newton (http://www.handprint.com/HP/WCL/color2.html#newtoncircle), 1704; **c.1750**: subtractive color wheel after , 1766; **c.1800**: perceptual color hexagram after Goethe (http://www.handprint.com/HP/WCL/goethe.html), 1807; **c.1850**: additive hue circle by Laugel, after Helmholtz, 1856/1869; **c.1900**: subtractive color triangle after Sloan (http://www.handprint.com/HP/WCL/color6.html#sloan), 1923; **c.1950**: subtractive color wheel by Famous Artist's School, 1958; Harris, Goethe and Laugel diagrams revised to place yellow at top

A long explanation could be provided for the conceptual and substantive differences among these color models, the audiences they were intended to address, the applications they were intended to serve, and the specific advantages or disadvantages each presents as a model of conceptual, visual or material color.

But the overarching lesson is the dominant, governing role of the three subtractive primary colors. The fact that these have only shows that traditional color theory has struggled to reconcile traditional artistic lore with evolving colorant manufacture technologies and continuing scientific advances in color research. This effort has pushed artistic color theory to emphasize conceptual colors, specifically "primary" colors, as a framework in which visual and material colors can coexist, and where any discrepancies between conceptual and material colors can be .

Hues in Modern Color Theory. Vision science, grappling with the technical difficulties of color measurement and color appearance modeling, and the diverse empirical problems created by color media and color imaging systems, has displaced "primary" colors with a factual description of *visual* hue relationships.

Why visual? Because visual color addresses most directly the relationship between the color stimulus and the color experience, and because "how a color looks" is the fundamental issue in any color image or color design. We don't care whether a red *is* saturated or yellowish, as material color: we only care whether it *appears* appropriately saturated or yellowish, given the image or visual context in which it is interpreted. And if we want to create that saturated red with a computer monitor, and printing inks, and paints, we do not want "saturated red" to be defined in terms of any specific material medium.

The visual trichromatic or "retinal" primary colors are not the primary colors of color appearance; they only have a role in bridging or connecting radiant colors to visual color appearance. The visual primary colors have been replaced by the opponent functions (http://www.handprint.com/HP/WCL/color2.html#opponentfunctions) that are associated with the hue contrasts *violet red/blue green* (**a**+/**a**) and *yellow/blue violet* (**b**+/**b**). These define the hue spacing shown in the diagram (below).

the modern primaries: the ab opponent dimensions

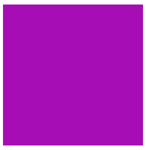
average hue locations on the CIECAM $\mathbf{a_C b_C}$ hue plane at lightness 6; letters R, Y, G, B and P indicate location of Hering unique hues (red, yellow, green, blue) and Munsell purple

These two dimensions do not privilege any "primary" hues, or of primary, secondary and tertiary hues. They simply regulate the spacing of visual hues around the hue circle. They reproduce the hue spacing determined through laborious research in the Munsell Color System (http://www.handprint.com/HP/WCL/color7.html#MUNSELL) and as defined by the CIECAM (http://www.handprint.com/HP/WCL/color7.html#CIECAM) color appearance model.

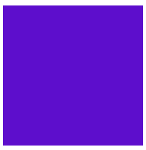
Literally any hue naming or hue categorization system can be imposed on this hue circle; the labels in the diagram above are based on my Handprint hue categories (http://www.handprint.com/HP/WCL/color13.html#huecategories), adapted from the hue naming system used by Moses Harris and exemplified by the hue circle diagram ().

Physical Hue Exemplars. As verbal categories are imprecise, it is helpful to have exemplars for color matching.

Below are visual color exemplars for the 18 hue categories as GIF files in standard 8 bit hex codes using the Photoshop color space in Mac OS X 10.5, standard cinema display palette and gamma. (Computer monitors differ in how well they reproduce absolute color samples, and reproduce greens, blue greens and violet reds poorly.) The "extraspectral" hues are titled in italics, and the nearest matching single pigment is suggested.



red violet
PV49



violet

PV23

blue violet

PV15 [blue shade]

violet blue

PB29

blue

PB35

green blue

PG36

blue green

PG7

green

PG36

yellow green

PY3+PG7

green yellow

PY184

yellow

PY35

orange yellow

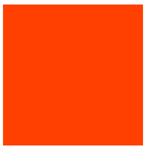
PY65

yellow orange

PY110

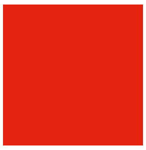
orange

PO20



red orange

PO73



orange red

PR188

red

PR209

violet red

PR122

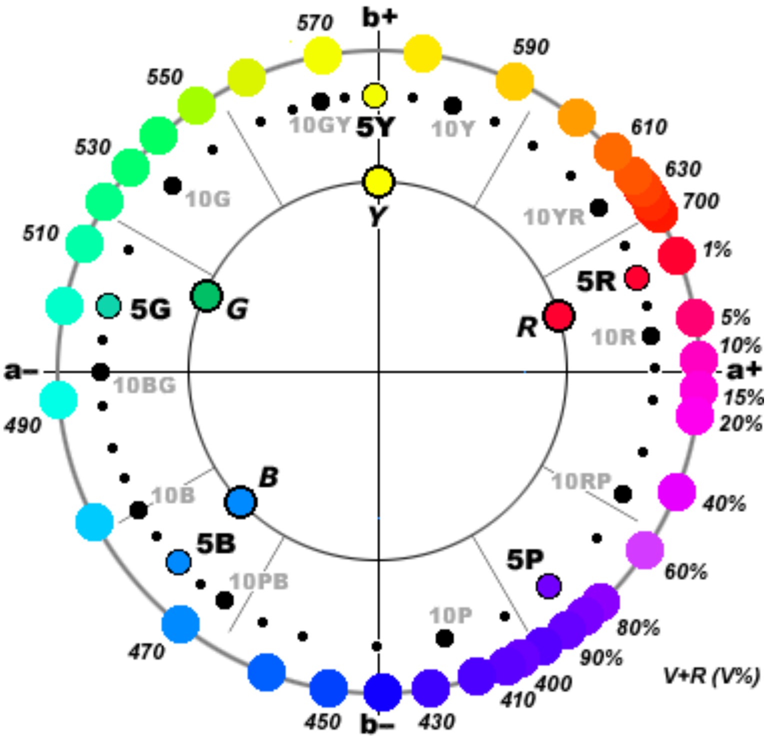
Next, here is how the visual hue circle distributes physical exemplars for the hue categories. The diagram (below) shows the hue circle location of:

(1) spectral wavelengths and extraspectral mixtures of "red" and "violet" light (in

color science, hues can be identified precisely by the matching hue of spectral light, called the **dominant wavelength**).

(2) the spacing of hue categories in the Munsell Color System, and

(3) the location of the four unique hues (red, yellow, green blue), as averaged across a number of color scaling experiments.

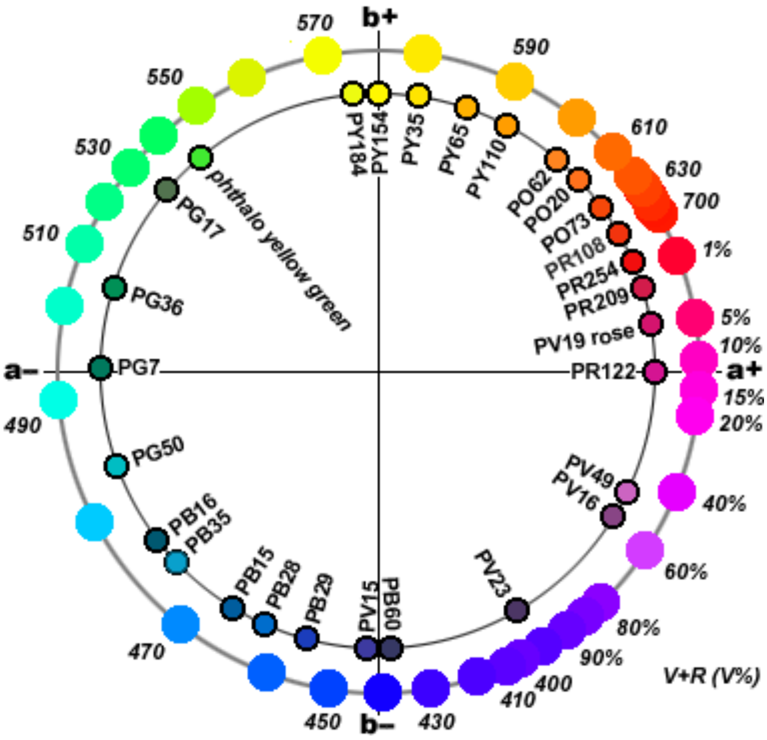


spectral wavelength and Munsell visual hue angles

average Munsell hue angle for all hues across values /6 to /8 and chromas /6 to /8, on the CIECAM $\mathbf{a_C b_C}$ plane

The spacing of spectral hues shows the increased wavelength discrimination that appears around "yellow" and "cyan" wavelengths, the decreased discrimination at the spectum ends and in the "green" wavelengths, and the strong tinting effect of "violet" light in the mixture of red and violet hues. It also vindicates Newton's original scaling of hues, which was developed using only the crudest of light manipulation tools.

The next diagram shows the spacing of common watercolor pigments on the visual hue circle, with spectral hues repeated for reference. (Note: all yellow hues appear in the spectrum, so the commercial watercolor paint name "spectrum yellow" is meaningless.)



spectral wavelength and pigment visual hue angles

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

This diagram illustrates very clearly the relative scarcity of green and violet pigments; very often, commercial watercolors in those hues colors must be mixed from green and yellow, or red and blue, pigments.

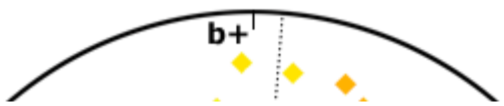
Complementary Hue Relationships. By adjusting the distance *between* hues around the circumference, the hue circle also determines which hues will be *directly opposite,* connected by a straight line that passes through the "white" center of the wheel. This again was explicitly noted by Newton:

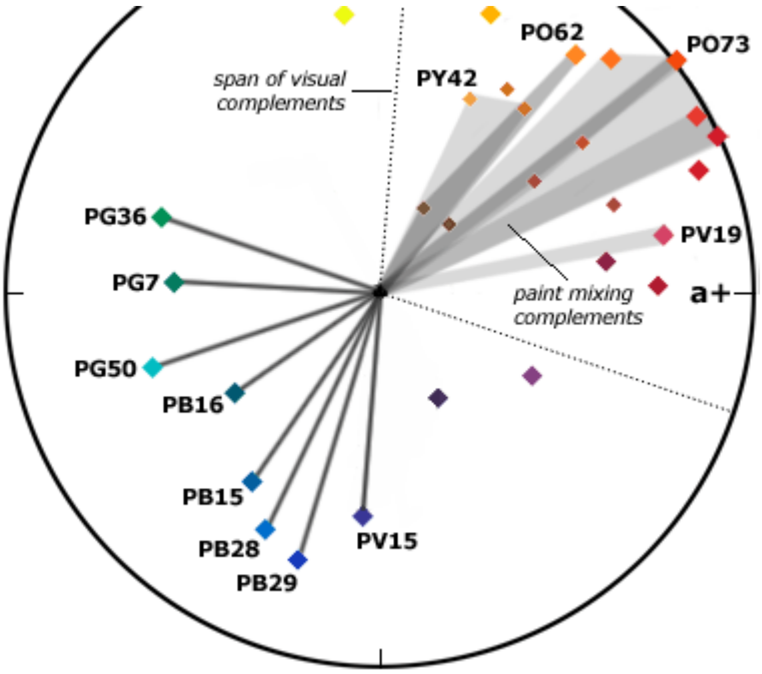
If only two of the primary Colours which in the circle are opposite to one another be mixed in an equal proportion, the [mixture] *shall fall upon the center." Opticks,* Book I, Proposition VI, Problem ii.

Newton observed that mixtures made with his seven "primary" colors did not create a pure white, but *"some faint anonymous Colour,"* which was because none of his hue wedges are directly opposite each other: all are skewed slightly to one side of "white". However in 1853 the German scholar Hermann Grassmann (http://www.handprint.com/HP/WCL/color2.html#grassmann) proved, and the vision scientist Hermann von Helmholtz (http://www.handprint.com/HP/WCL/color6.html#helmholtz) quickly demonstrated, that the appropriate pair of *individual* light wavelengths must and can mix an achromatic white. These wavelengths define visual complementary hues (http://www.handprint.com/HP/WCL/color16.html#complement).

When artists replaced Newton's light "primaries" with primary colors of paint, they also redefined complementary hues to be those hues of paints that, when mixed in the appropriate proportions, create an achromatic gray or black. These paints define mixing complementary hues (http://www.handprint.com/HP/WCL/color13.html#compprobs).

The difference between radiant and material colors intrudes again in complementary color mixtures: the pairing of complementary hues defined by light mixtures (which produces white light) is significantly different from the complementary pairs defined by paint mixtures (which produce black paint), as summarized in the diagram (below) of the mixing complementary relationships as they appear on a visual chromaticity plane.





mixing vs. visual complements

pigment locations on the CIECAM $\mathbf{a_C b_C}$ plane

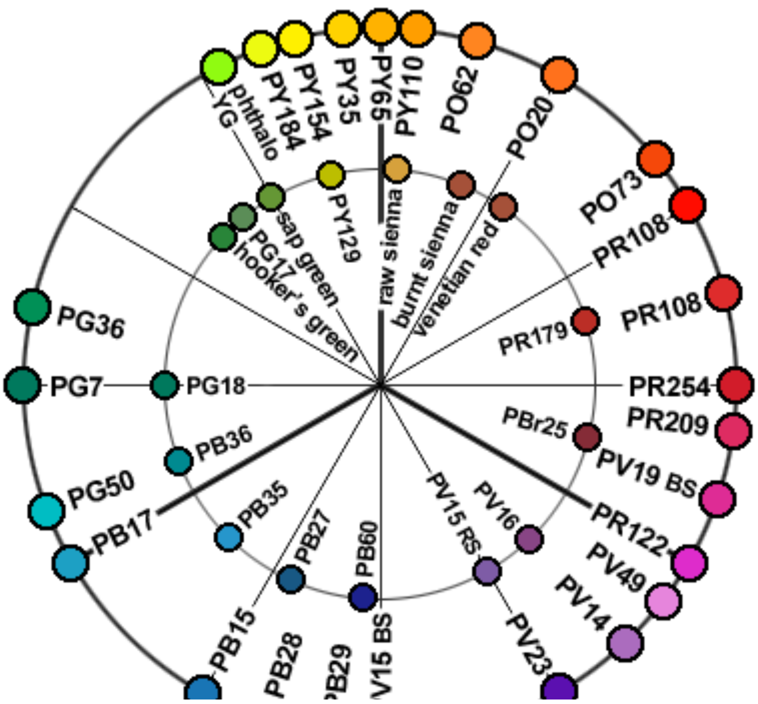
The diagram shows that the visual colors of paints from *blue violet* (ultramarine violet, PV15 (http://www.handprint.com/HP/WCL/waterv.html#PV15)) to *green* (phthalo green YS, PG36 (http://www.handprint.com/HP/WCL /waterg.html#PG36)) create a span of visual complements that extends from *yellow* to *red violet*. But the mixing complements for these paints cover a much smaller hue span, roughly from *yellow orange* (yellow ochre, PY42 (http://www.handprint.com/HP/WCL/watere.html#PY42)) to *violet red* (quinacridone rose, PV19 (http://www.handprint.com/HP/WCL /waterc.html#PV19R)).

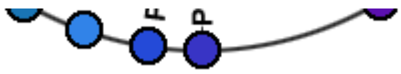
These differences occur because *violet blue* paints, such as ultramarine blue (PB29 (http://www.handprint.com/HP/WCL/waterb.html#PB29)), contain more blue+green than red (http://www.handprint.com/HP/WCL/IMG/RC /rcPB29.jpg) reflectance, so the visual complement *yellow* must be shifted toward red, to contain more red than blue+green (http://www.handprint.com/HP/WCL

/IMG/RC/rcPY43.jpg) reflectance and create a balance in subtractive mixture. On the other hand *green* paints, such as phthalo green YS (PG36 (http://www.handprint.com/HP/WCL/waterg.html#PG36)) contain more blue+green than red (http://www.handprint.com/HP/WCL/IMG/RC /rcPG7.jpg) reflectance, so the visual complement *red violet* must be shifted toward red, to contain more red than blue+green (http://www.handprint.com /HP/WCL/IMG/RC/rcPV19r.jpg) reflectance to compensate.

Mixing complements roughly match the visual complements for hues such as *yellow green/violet* and *red orange/green blue,* but we clearly must choose one or the other system, especially for color design work.

Many painters, adhering to 18th century color prejudice, prefer a hue circle or color wheel defined by paint mixtures. But these "mixing color wheels" are plagued with practical shortcomings, summarized on this page (http://www.handprint.com/HP/WCL/color16.html#mixprobs). As a point of reference, the diagram (below) shows a typical mixing color wheel, based on my exhaustive table of watercolor mixing complements (http://www.handprint.com /HP/WCL/mixtable.html), to illustrate some of the problems.





a mixing complement hue circle

saturated paints on the circumference, less saturated paints on the inner circle

The main problems with subtractive mixture hue circles are:

The core problem is the between mixing complements: this means that paints with the same mixing complement relations but very different visual hues must be placed in the same hue location, or that paints with the same visual hue but different mixing complement relations must be spaced apart.

As indicated in the diagram (above), subtractive hue circles must allot a quarter of the hue circle to hues from *red* to *yellow orange* in order to represent the complement relations with the much larger span of hues from *blue violet* to *blue green*

Subtractive hue circles force an erratic spacing of hues (very large gaps between *yellow green* and *green,* or between *blue* to *green blue,* and a very compressed spacing from *yellow orange* to *green yellow* or from *violet blue* to *blue*)

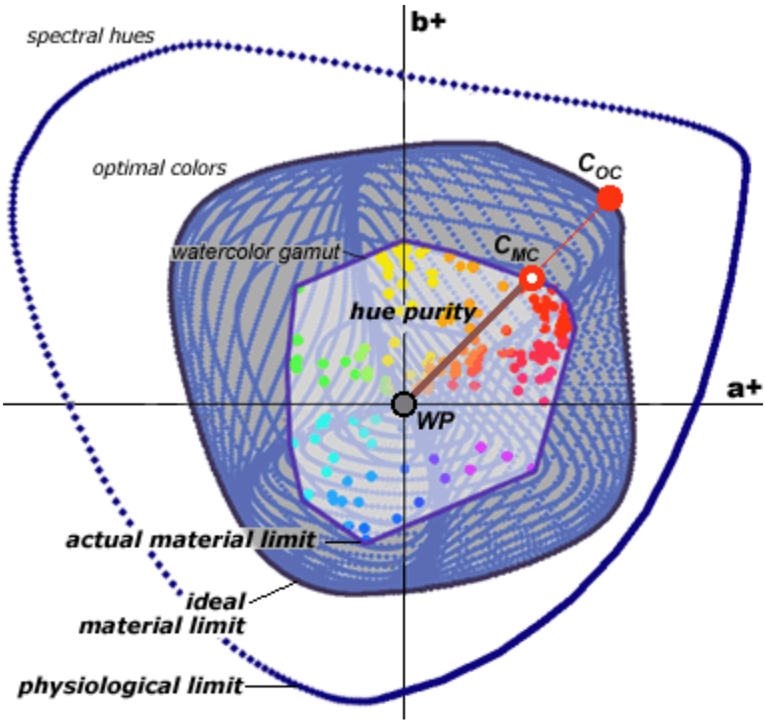
The spacing of hues that results does not represent the perceptual difference between them (very similar hues are spread far apart, very different hues are pressed close together)

To reconcile these discrepancies, many arbitrary decisions have to be made about the spacing between hues: different painters, using the same mixing complement information (http://www.handprint.com/HP/WCL/mixtable.html), will usually produce different hue spacings around the hue circle.

Chroma Relationships. Chroma has been the most neglected colormaking attribute in traditional color theory. In part this is because the study of color relationships has focused on and "pure" primary colors.

However, another reason chroma has been neglected is that it is a hybrid color attribute that combines aspects of lightness/brightness and hue; separately manipulating lightness and hue limits chroma variations in important ways. To understand these issues it is necessary to view chroma as influenced by three separate factors relative luminance, changes in lightness across all hues, and changes in lightness within a single hue.

Relative Luminance & Chroma Boundaries. Chroma or saturation inhabits three different realms of color experience, articulated by the between lights and surfaces, and between ideal and real physical surfaces (diagram, below).



three fundamental chroma boundaries

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

Individual spectral wavelengths, presented at adequate luminance in a dark surround, produce the most saturated visual color sensations possible in a radiant color. They illuminate the *physiological limits* of chroma sensation: the structure of our visual system makes it impossible to perceive a greater or more intense hue purity. We see hues of this intensity, for example, in prismatic colors, lasers, the setting sun, transmissive colors in gems or stained glasses, or saturated surface colors viewed under high .

These color stimuli all appear with the sensation of *brightness,* and part of their hue purity arises because they do not have the *blackness* inherent in surface colors viewed within a single light environment. The theoretical boundary between lightness and brightness is defined by optimal colors (http://www.handprint.com/HP/WCL/color3.html#optimalstimuli), which have the highest hue purity possible for a nonfluorescent surface color of a given hue and lightness. We commonly see isolated visual colors comparable to optimal colors in saturated surfaces under moderate illuminance contrast.

At still lower levels of chroma are reflective material colors, including all artists' pigments, that present some blackness or grayness under normal viewing conditions. I have defined the color attribute hue purity (http://www.handprint.com/HP/WCL/color3.html#huepurity) as the chroma of a material color divided by the chroma of the optimal color of matching hue and lightness, or (in the diagram, above):

$HP = C_{MC} / C_{OC}$

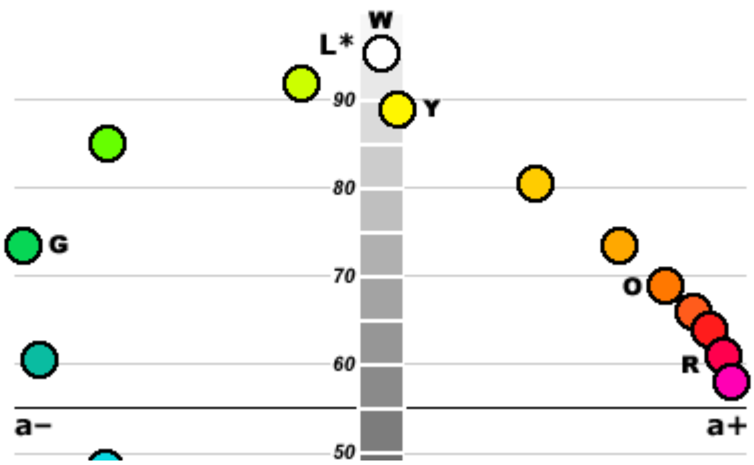
I have tabulated here (http://www.handprint.com/HP/WCL/huepurity.html) the hue purity values of 170 watercolor pigments; in general, hue purity correlates very well with CIECAM chroma.

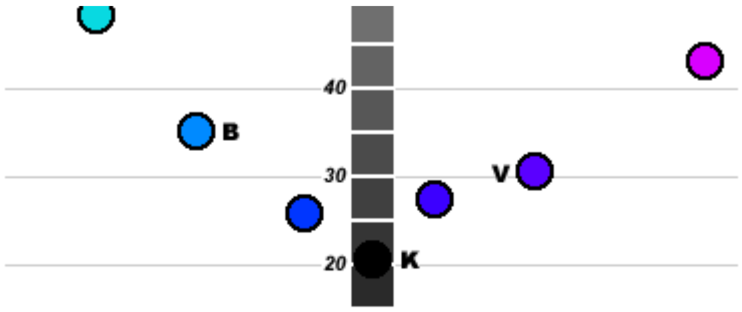
The point here is that visual chroma depends on how a color is illuminated and how that illumination is interpreted. In general, the range of chroma is greater for lights than for material surfaces, and our visual judgments of chroma depend importantly on how we interpret surface illumination. To the extent that we can "see" that the brightness of a color is due to the illuminance it receives, we discount that brightness as an attribute of the material color.

Chroma & Lightness Across Hues. The lightness or value at which a hue reaches its maximum chroma is different around the hue circle. Hues near *yellow* reach their peak chroma only when they are at a very high lightness, and hues near *blue violet* reach their peak chroma only when they are very dark.

This relationship roughly matches the relative luminance of the individual hues as they appear in the spectrum, for example as their contribution to a photopic sensitivity function (http://www.handprint.com/HP/WCL /color1.html#newpsf). The major exceptions are in *violet* to *violet red* hues, which are spectral mixtures and are brighter than spectral *blue violet*.

These variations are very nicely distributed along the **a+/a** dimension, as displayed in the artist's value wheel (http://www.handprint.com/HP/WCL /vwheel.html) for most common watercolor pigments, and as measured in the CIECAM color space using a 70 nm optimal circuit, as explained in the synthesis of surface colors (http://www.handprint.com/HP/WCL /color19.html#70circuit) (diagram, below).



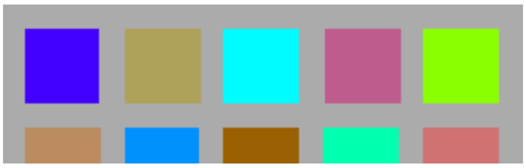


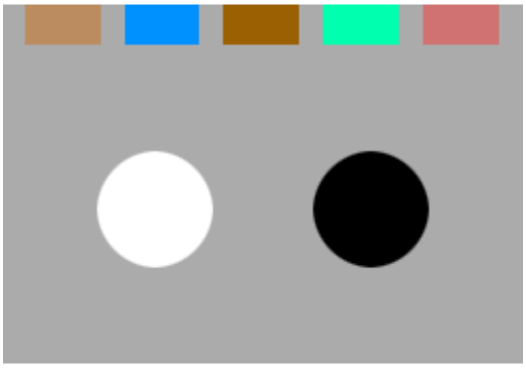
lightness of peak chroma in 18 hue categories

the lightness at which different hues reach their peak chroma in optimal colors, distributed by red/green (**a**+/**a**) content and mapped into a watercolor pigment gamut (**L*** = 95)

The major implication of these relationships is in the mapping of hues into a value design. Dark valued areas of an image simply cannot be rendered as a pure saturated green or orange; the green or orange can be saturated, but at darker values they will appear dull or (in orange) as brown. The clearest mapping of hue to value appears in medieval and certain modernist painting styles (late Van Gogh, Matisse, Derain, Ellsworth Kelly, etc.), where pure pigment colors are used much more than mixed colors or colors darkened with black.

This relationship between peak chroma and lightness is the reason traditional color theory claims that "warm" hues advance (http://www.handprint.com/HP/WCL/color11.html#warmeffects) and "cool" hues recede. In fact this visual effect has almost nothing to do with hue. It occurs because red, orange and yellow pigments have a higher saturation (http://www.handprint.com/HP/WCL/cwheel06.html) than all other pigments (with the exception of some convenience yellow greens), and because at their peak saturation they are much lighter valued than nearly all green, blue and violet pigments.





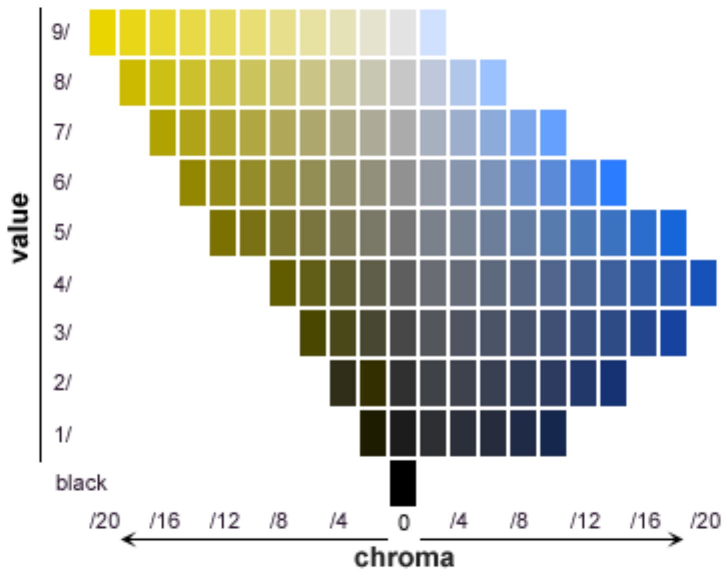
warm color effects caused by lightness and/or chroma

cool colors can easily appear "advancing" or "arousing" if they are lighter and/or more intense than the warm colors around them; a white disk appears "closer" than a black disk

The diagram (above) shows that we can easily make "cool" greens and blues appear to advance, or to be more "arousing", if we manipulate them to have a higher chroma or lightness than the "warm" hues they are paired with. The fact that a white disk appears to "advance" in relation to a black disk shows that the effect is independent of chromaticity.

Chroma & Lightness Within Hues. The modern geometrical color framework implies that we can change one colormaking attribute without changing the other two. This is true only in one sense: we can always reduce the chroma of any color toward gray without changing its hue or its lightness.

In practice, the changes possible in one colormaking attribute are limited by the value of the other two attributes. Thus, it is not possible to make a pastel blue paint more chromatic without also making it darker, or to make a saturated yellow darker without reducing its chroma. The diagram (below) contrasts these limitations between two visual complementary hues of yellow and violet blue, as displayed in color samples from the Munsell Color System.



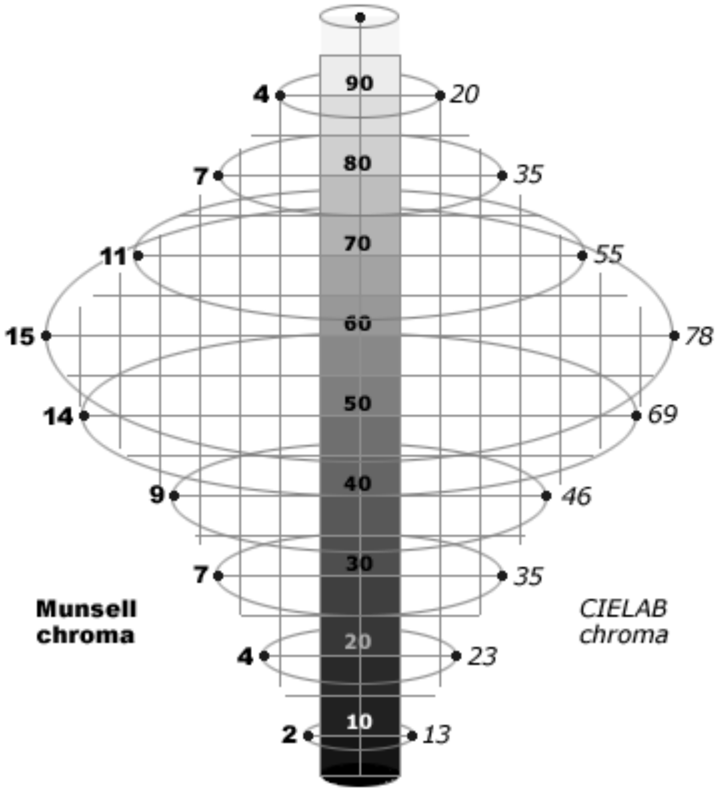
chroma and lightness boundaries in yellow & blue paints

as defined in the Munsell Color System (http://www.handprint.com/HP/WCL/color7.html#MUNSELL)

Similar diagrams for other hue slices would show the same bulging contour: hues taper to achromatic at extreme white and black lightness, and bulge to their maximum chroma at some middle lightness. The previous diagram showed where that bulge is located on a lightness scale, but the exact shape of the bulge, and the lightness of the peak chroma, vary widely across hues (diagram, right).

Obviously, increasing the lightness variation in an image usually forces some hues to have low chroma, and using all hues at high chroma limits the range of lightness values that each hue can represent: light valued figures must be yellow, orange or yellow green; dark valued figures must be blue or violet. The French painter André Derain turned this second limitation into a painting style (http://en.wikipedia.org/wiki/Andr%C2%8E_Derain).

The lightness/chroma interaction comes to the fore when the painter or photographer tackles the problem of gamut mapping (http://www.handprint.com/HP/WCL/color11.html#paintzone). It also has implications for color design. A widely recommended technique for producing color harmony is to render all hues at a very similar lightness and chroma; this is nuance matching (http://www.handprint.com/HP/WCL/color17.html#nuance). But it is not possible to match a light valued, saturated yellow with a light valued, saturated blue. So any combination of hues can be selected to have the same nuance (the same chroma and lightness) only within a spindle shaped core of the color space (diagram, below).

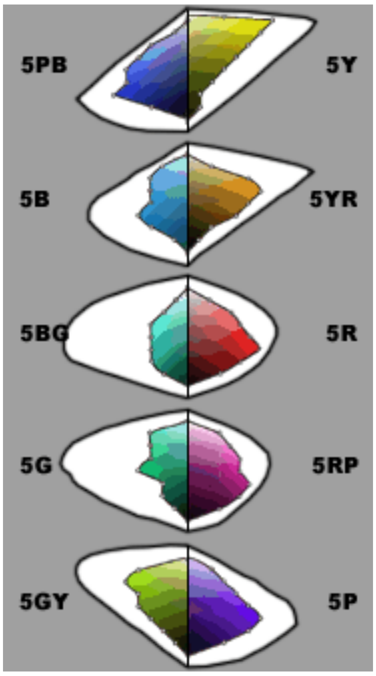


the nuance space

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

This diagram was developed using optimal colors; the nuance matching possible with pigments will necessarily be smaller (compare diagrams, above right), though its general form will be the same: the widest variety of nuance matches are possible in the middle lightness values, and in light or dark valued colors only at a very reduced (dull) chroma.

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



maximum chroma of
munsell color samples

shown within optimal color limits for the same hues (white area); after Kuehni (2003) and Perales, Mora et al. (2004)